More than the shoulder? Kinematics of the jump throw and factors influencing shoulder problems in handball

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Thesis for the degree of Philosophiae Doctor

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Meira en bara öxlin? Hreyfigreining á uppstökkskasti og áhrifaþættir axlarmeiðsla í handbolta

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Ágrip

Markmið: Axlarmeiðsli eru algeng á meðal handboltaiðkenda og á meðal þekktra áhættuþátta eru skortur á styrk og hreyfigetu í öxl og skyndileg aukning í æfinga- og keppnisálagi. Kasthreyfingin er stór, framkvæmd með öllum líkamanum og rannsóknir hafa sýnt að kraftmyndun í neðri útlimum og bol tengist kasthraða. Áhrif styrks og afls í neðri útlimum og bol á þróun axlarmeiðsla í handbolta hafa hins vegar ekki verið könnuð í framskyggnum rannsóknum. Áhrif innra álags á öxl (sjálfsmat á álagi) samanborið við ytra álag (metið með t.d. fjölda skota í leik) á þróun meiðsla í kastöxl yfir keppnistímabil hafa ekki verið könnuð á meðal handboltaiðkenda. Þrátt fyrir að uppstökk sé ein algengasta kasttæknin í handbolta hafa fáar rannsóknir greint hana með þrívíddartækni. Áhrif hreyfinga í neðri útlimum og bol á kastöxlina eru því lítið þekkt sem og áhrif leikstöðu. Markmið þessa doktorsverkefnis var því í megindráttum tvíþætt; að kanna tengsl á milli grunnstyrks og afls í neðri útlimum og bol og axlarmeiðsla yfir heilt handboltatímabil og að greina hreyfimynstur í uppstökkskasti með þrívíddarhreyfigreiningu. Einnig var innra og ytra álag á kastöxl áætlað yfir tímabilið til að meta hvor mæling hefði sterkari tengsl við axlarmeiðsli. Aukin þekking á sviðinu mun gefa sterkari forsendur fyrir meiðslaforvarnir í gegnum álagsstýringu, hvort sem er í gegnum grunnstyrk og kasttækni eða með temprun á keppnis- og/eða æfingaálagi.

Aðferðir: Framkvæmd rannsóknanna sem þessi ritgerð byggir á var þrískipt. Þátttakendur í fyrsta hlutanum voru 42 leikmenn úr efstu deild karla í handbolta. Mælingar á hámarksstyrk í neðri útlimum, hámarkssnúningsafli í bol og hámarkssnúningsstyrk í kastöxl voru framkvæmdar fyrir keppnistímabilið 2022-2023. Þátttakendum var í kjölfarið fylgt eftir í gegnum heilt keppnistímabil (31 vika) þar sem þeir svöruðu vikulega spurningalista sem var sérstaklega hannaður til að kanna umfang og alvarleika álagsmeiðsla. Að auki svöruðu þeir vikulega spurningu varðandi mat á huglægu álagi á kastöxl síðastliðna viku (innra axlarálag). Þátttakendur í öðrum hluta voru 31 leikmaður úr efstu deild kvenna í handbolta. Sömu mælingar og í fyrsta hluta voru framkvæmdar fyrir keppnistímabilið 2023-2024 og var þátttakendum aftur fylgt eftir í gegnum heilt keppnistímabil (29 vikur). Þátttakendur svöruðu einnig vikulega sama spurningalista og viðbótarspurningu um innra axlarálag og í fyrsta hluta. Að auki voru upplýsingar um fjölda skota í deildarleikjum fyrir hvern þátttakenda teknar saman til þess að leggja mat á ytra axlarálag. Tengsl á milli styrktar- og aflmælinga á undirbúningstímabili og algengi og alvarleika álagsmeiðsla í öxl voru metin með Spearman´s rho fylgnistuðli fyrir þátttakendur úr fyrsta og öðrum hluta. Áhrif styrktar- og aflmælinga á tengsl innra og ytra axlarálags og alvarleika axlarmeiðsla voru einnig könnuð með blandaðri dreifnigreiningu. Í þriðja hluta var framkvæmd þrívíddarhreyfigreining á uppstökkskasti hjá 41 leikmanni úr efstu deild karla og fór hún einnig fram fyrir keppnistímabilið 2022-2023. Tengsl á milli hreyfinga í neðri útlimum og bol og hreyfinga í kastöxl við framkvæmd kasts eftir uppstökk voru metin með Pearson´s og Spearman´s rho fylgnistuðlum. Óháð *t*-próf voru notuð til að meta mun á framkvæmd á milli leikmanna eftir leikstöðu og áhrif hreyfinga í neðri útlimum og bol á hornhraða innsnúnings í kastöxl voru metin með þrepaskiptri aðhvarfsgreiningu.

Niðurstöður: Niðurstöður úr fyrsta hluta rannsóknar (karlkyns leikmenn) sýndu fram á tölfræðilega marktæka (neikvæða) fylgni á milli hámarksútsnúningsstyrks í öxl og algengi axlarmeiðsla yfir tímabilið (r_s=-0.34, p=0.029). Innra axlarálag hafði marktæk áhrif á alvarleika axlarmeiðsla (p<0.001), þar sem aukið innra axlarálag tengdist auknum alvarleika axlarmeiðsla. Marktæk víxlhrif voru á milli innra axlarálags og snúningsafls í bol (p=0.017) varðandi áhrif þeirra á alvarleika axlarmeiðsla. Karlkyns leikmenn með hámarkssnúningsafl í bol einu staðalfráviki fyrir neðan meðaltal hópsins skráðu alvarlegri axlarmeiðsli eftir því sem innra axlarálag jókst. Niðurstöður úr öðrum hluta rannsóknar (kvenkyns leikmenn) sýndu jákvæða fylgni á milli algengi axlarmeiðsla og hámarksstyrks í neðri útlimum (r_s=0.40, p=0.03) og hámarksútsnúningsstyrks (r_s=0.38, p=0.04) í öxl. Innra axlarálag hafði marktæk áhrif á alvarleika axlarmeiðsla þar sem aukið álag tengdist auknum alvarleika axlarmeiðsla (p<0.001). Neikvætt samband var hins vegar á milli ytra axlarálags og alvarleika axlarmeiðsla (p=0.04). Marktæk víxlhrif voru á milli innra axlarálags og þriggja styrktarmælinga varðandi áhrif þeirra á alvarleika axlarmeiðsla. Kvenkyns leikmenn með hámarksstyrk sem nam einu staðalfráviki fyrir ofan meðaltal hópsins í neðri útlimum, útsnúningsstyrk í öxl, og snúningsafl í bol, tilkynntu alvarlegri axlarmeiðsli eftir því sem innra axlarálag jókst. Niðurstöður þrívíddarhreyfigreiningar á uppstökkskasti hjá körlum sýndu að hornhraði og hreyfiútslag í mjöðmum og mjaðmagrind útskýrðu 44% af breytileika á innsnúningshornhraða í kastöxlinni. Einnig kom fram að miðjumenn og skyttur voru með marktækt hærri hornhraða í öllum mælingum fyrir utan í bolsnúning og með stærra hreyfiútslag í mjöðmum, mjaðmagrind og bol miðað við horn- og línumenn.

Ályktanir: Niðurstöðurnar gefa til kynna að lægra útsnúningsafl í bol við upphaf tímabils hjá karlkyns leikmönnum geti gert kastöxlina útsettari fyrir álagsmeiðslum við mikið innra axlarálag yfir tímabilið. Karlkyns handboltaiðkendur ættu því að leggja áherslu á þjálfun bolsnúningsafls á undirbúningstímabili. Niðurstöðurnar varpa hins vegar ljósi á flókið samspil mismunandi áhættuþátta varðandi axlarmeiðsli á meðal kvenkyns leikmanna og gefa að auki til kynna að innra axlarálag sé betri mælikvarði en ytra axlarálag hvað varðar líkleg áhrif á meiðsli. Niðurstöðurnar sýna einnig fram á mikilvægi kraftmyndunar í neðri útlimum og bol fyrir hagkvæma framkvæmd á uppstökki og að ólíkar kröfur mismunandi leikstaða spili inn í mun á hámarkshornhraða og hreyfiútslagi við framkvæmd á uppstökki. Mikilvægt sé því að skipuleggja styrktarþjálfun í takt við þau hlutverk sem leikmaðurinn þarf að leysa inni á vellinum.

Lykilorð:

Axlarálag, álagsmeiðsli, forvarnir meiðsla, hreyfikeðja, kasthreyfing.

Abstract

Aims: Shoulder problems are common in handball and known risk factors include decreased shoulder rotational strength, limited shoulder rotational mobility, and sudden increases in training and competition load. The throwing motion is a large movement, and previous research has linked proximal segments´ force production to throwing velocity. Nevertheless, the influence of lower body strength and trunk rotation power (TRP) on shoulder problems in handball players has not been investigated prospectively. Similarly, the association between internal shoulder load (subjective perception of load) vs. external shoulder load (e.g. number of throws in a match) measurements and shoulder problems among handball players is unknown. Despite the jump throw being the most common throwing technique in handball, very few motion analyses of it have been conducted. Moreover, the extent to which proximal segments' kinematics influence more distal segments, such as the shoulder, is unknown, as are possible kinematic differences between different positions. The aims of this thesis were to examine the association between pre-season strength and power in the lower body and trunk, and shoulder problems among handball players, to perform a 3D motion analysis of the jump throw and, to investigate whether internal or external shoulder load measurements were more consistently associated with shoulder problems. Increased knowledge of this topic might influence injury prevention via better load management, either by ensuring adequate pre-season strength and power or by regulating training/competition shoulder load.

Methods: This thesis is based on results from three research papers. Paper I included 42 male handball players. Pre-season measurements of peak lower body strength, peak trunk rotation power (TRP), and peak external and internal rotation strength in the throwing shoulder were conducted before the 2022–2023 season. Participants were followed throughout a whole regular season (31 weeks), where they answered a weekly questionnaire specially designed to document the prevalence and severity of overuse problems, and an additional question regarding participation-related shoulder load (PSL – subjective experience of shoulder load (internal load)) during the previous week. Paper II involved 31 female handball players. The same pre-season protocol as used in paper I was conducted before the 2023–2024 season and participants answered the same questionnaire throughout the season (29 weeks). Performance data, including the total number of shots per player in all league matches were collected from HBstatz (official statistical provider for the Icelandic Handball Federation) and defined as external shoulder load. For paper I and II, the association between pre-season strength and power and the prevalence and severity of shoulder problems was assessed with the Spearman´s rho correlation coefficient. The influence of pre-season strength and power on the association between internal and external shoulder load, and the severity of shoulder problems was examined with a mixed model ANOVA. Paper III involved a 3D motion analysis of 41 male top-division players performing a jump throw, conducted before the 2022—2023 season. The correlation between proximal and distal segments´ kinematics was assessed and differences in jump throw kinematics between playing positions were analysed with an independent *t*-test. The explanatory strength of proximal segments´ kinematics on the variance in shoulder internal rotation (IR) angular velocity was assessed by using a stepwise regression model.

Results: The results from paper I (male players) showed a negative correlation between pre-season ER strength and the prevalence of shoulder problems (r_s=-0.34, p=0.029). A main effect was observed showing a positive relationship between PSL and the severity of shoulder problems (p<0.001). A significant interaction was observed between PSL and pre-season TRP in terms of their influence on the severity of shoulder problems, as males with pre-season TRP one standard deviation (SD) below the group´s mean had a stronger association between the severity score and PSL. The findings from paper II (female players) showed a positive correlation between peak lower body strength (r_s=0.40, p=0.03) and peak ER shoulder strength (r_s=0.38, p=0.04), and the prevalence of substantial shoulder problems. A main effect was again observed for PSL, with higher PSL associated with higher severity score (p<0.001). However, a negative association was found between the external shoulder load and the severity of shoulder problems (p=0.04). A significant interaction was observed between PSL and peak lower body strength, TRP, and ER shoulder strength in terms of their influence on the severity of shoulder problems. Female players with pre-season strength and power one SD above the group´s mean showed a stronger association between the severity score and PSL. Paper III showed that hip and pelvis kinematics explained 44% of the variance in shoulder IR angular velocity. Significant differences were found between positions with center/back players displaying higher angular velocities in all measured segments, except trunk rotation, and greater range of motion excursion in the hips, pelvis, and trunk compared to wing/pivot players.

Conclusions: The findings suggest that low pre-season TRP in male players may make the throwing shoulder more vulnerable for an increase in load. Pre-season training should therefore emphasize TRP training for male players. However, the results highlight the complex interaction between multiple risk factors for shoulder problems in female players and suggest that PSL (internal load) is more consistently associated with shoulder problems in handball, compared to external load. The results also underscore the role of proximal segments´ kinematics in terms of an efficient jump throw performance, and that different on-field demands likely influence kinematic differences between central/back vs wing/pivot players. It is therefore important to tailor strength training accordingly to each player's on-field demands.

Keywords:

Injury prevention, kinetic chain, overuse injuries, shoulder load, throwing motion.

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Contents

List of Abbreviations

ER = External rotation

IR = Internal rotation

TRP = Trunk rotation power

IMTP = Isometric mid-thigh pull

OSTRC-O2 = Oslo Sports Trauma Research Center Overuse Injury Questionnaire

GIRD = Glenohumeral internal rotation deficit

ACWC = Acute vs chronic workload ratio

PSL = Participation-related shoulder load

ROM = Range of motion

SD = Standard deviation

SE = Standard error

GH = Glenohumeral

MER = Maximum external rotation

SEM = Standard error of measurement

CV = Coefficient of variation

MDD = Minimal detectable difference

BW = Body weight

DF = Degrees of freedom

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List of Original Papers

This thesis is based on the following original publications, which are referred to in the text by their Roman numerals (I, II, III):

I. Árnason, K., Ágústsson, A., Fredriksen, H., Rafnsson, E., Briem, K. (2024) Let´s swing it. The interaction between participation-related shoulder load and pre-season trunk rotation power on shoulder problems in male handball players. Int. J. Sports Phys. Ther. 19(12):1541-1550. doi:10.26603/001c.126187

II. Árnason, K., Ásgeirsdóttir, E., Arnarsson, U., Ágústsson, A., Briem, K. (2025). The association between internal and external shoulder load, the pre-season strength and power, and shoulder problems in female handball players. Int. J. Sports Phys. Ther. 20(8):1203-1213. doi.org/10.26603/001c.142239.

III. Árnason, K., Ágústsson, A., Briem, K. (2025). The jump throw proximal-to-distal sequence. Contribution of the proximal segments to the shoulder kinematics. Submitted for publication in the Journal of Applied Biomechanics in June 2025.

In addition, some unpublished data are presented.

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Declaration of Contribution

Paper I

Kári Árnason (KÁ) designed the study, recruited participants and conducted the data collection. The data analysis was done in collaboration with dr. Kristín Briem (KB) and Dr. Atli Ágústsson (AÁ) with assistance from Dr. Þórarinn Sveinsson (ÞS). The manuscript was written by KÁ and edited by KB, AÁ, Dr. Hilde Fredriksen and Dr. Elís Thor Rafnsson.

Paper II

KÁ designed the study in collaboration with KB. Erla Ásgeirsdóttir (EÁ) and Unnar Arnarsson (UA) recruited participants and conducted the data collection in collaboration with KÁ. Data analysis was done by KÁ, EA, UA, KB, AÁ with assistance from ÞS. The manuscript was written by KÁ and edited by KB and AÁ.

Paper III

KÁ designed the study in collaboration with KB and AÁ, recruited participants and conducted the data collection. Data processing and analysis was done by KÁ, KB and AÁ. The manuscript was written by KÁ and edited by KB and AÁ.

1 Introduction

The throwing motion has been around for thousands of years and is believed to have had a significant effect on the evolution of modern human beings (homo sapiens). Human beings throw with incredible power and accuracy, with the shoulder rotational angular velocity during a baseball pitch recorded to be approximately 9000 degrees per second (°/s). Originally, the purpose of throwing was thought to be a defensive one so our ancestors could defend themselves from predators but over time developed into an effective hunting strategy. Being able to hunt larger animals from a safe distance led to the consumption of calorie rich food which supported further development of muscles, bones and brain tissue. The following maturation of the brain tissue is thought to have provided the necessary foundation for the development of language and human communication skills (Lewis, 2022). The modern use of the throwing motion is primarily through participation in various overhead sports, with the general sports fan often being left in awe of the incredible ability of elite athletes to throw repetitively with great speed and precision.

1.1 Shoulder problems in handball

Lately, the game of handball has received more attention, both in the form of an increased popularity among the general public, and from a scientific perspective. Handball is a physically challenging sport, unique in the sense that high load is placed on the athlete´s shoulder in the form of intensive and repetitive throwing, tackling and collision. Various throwing techniques are used during offense, with the end goal of getting the ball past the defenders and goalkeeper of the opposing team, and into the net. It should therefore not come as a surprise that shoulder problems are common among handball players (Andersson et al., 2017; Asker et al., 2018; Clarsen et al., 2014; Myklebust et al., 2013; Rafnsson et al., 2021). The prevalence of shoulder problems has been reported to be between 17-28% and the prevalence of substantial shoulder problems (defined as problems causing moderate/severe reduction in training volume, or moderate/severe reduction in performance, or complete inability to participate (Clarsen et al., 2013)) to be to between 5-12% among elite players (Andersson et al., 2017; Clarsen et al., 2014). The prevalence of shoulder problems and substantial shoulder problems among adolescent handball players has been reported to be even higher, or 44% and 23%, respectively, with female players showing both a higher prevalence of shoulder problems and substantial problems compared to males (Asker et al., 2018). Female players have also been shown to have a higher incidence of shoulder problems in the dominant arm (Asker et al., 2020) and to be at greater risk of sustaining traumatic injuries compared to male players (Giroto et al., 2017). Moreover, results from Myklebust et al. (2013), on

Norwegian female players, showed that a significantly higher proportion of players with shoulder pain had clinical signs of shoulder instability compared to those without pain.

When looking at different phases of the handball season, the prevalence of shoulder problems has been reported to be particularly high during the pre-season phase. Rafnsson et al. (2021) recently reported the weekly pre-season prevalence of shoulder problems to be 40% among Icelandic elite male players and in a study on Norwegian female elite players, Myklebust et al. (2013), reported pre-season prevalence of shoulder pain to be 36%.

1.2 Risk factors for shoulder problems

Identifying the "right" risk factors for injuries in sports and the appropriate preventative measures can be described as being the holy grail in sports medicine. However, whether sports medicine clinicians and researchers will ever find it remains to be seen but one can argue that as long as the search continues, we get closer and closer to finding it. One can also argue that participation in any physical activity is a risk-taking behavior, particularly in high-speed sports like handball, so injuries will evidently remain a part of the game.

Risk factors for injuries in sport have been described as modifiable and non-modifiable, with a recent systematic review looking at risk factors for shoulder problems in various overhead sports concluding that most identified risk factors, such as sex, were non-modifiable (Asker et al., 2018). However, studies looking at potential risk factors for shoulder problems specifically among handball players have identified multiple modifiable risk factors among elite and adolescent players. These include e.g. reduced external rotation (ER) strength (Achenbach et al., 2020; Clarsen et al., 2014; Moller et al., 2017), reduced internal rotation (IR) shoulder strength (Asker et al., 2020), reduced IR range of motion (ROM) and increased ER ROM in the throwing shoulder (Almeida et al., 2013), scapular dyskinesis (Asker et al., 2020; Clarsen et al., 2014; Moller et al., 2017) and a low ER/IR ratio (Asker et al., 2020). Studies have also shown prevention programs specifically designed to reduce the prevalence of shoulder problems and shoulder injury rate among handball players, by addressing e.g. ER strength, to be effective (Andersson et al., 2017; Asker et al., 2022). Those results are in line with a systematic review looking at the effectiveness of exercise interventions on overuse injuries, indicating that strength training, in general, could reduce overuse injuries in sports by almost a half (Lauersen et al., 2014).

One of the most prevalent modifiable risk factors for shoulder problems in overhead athletes is reduced IR ROM or "Glenohumeral internal rotation deficit" (GIRD) (Fares et al., 2024).GIRD has been defined as decreased IR ROM that is larger than the adaptive increase in ER ROM in the throwing arm compared to the non-throwing arm (Burkhart et al., 2003) and has repeatedly been associated with shoulder pain among both handball players and baseball pitchers (Almeida et al., 2013; Myers et al., 2006; Ruotolo et al., 2006). GIRD is believed to be the consequence of repetitive forceful overhead throwing (Burkhart et al., 2003) but the shoulder IR angular velocity, during an overhead handball throw, has been reported to be roughly 5000 °/s (Wagner et al., 2010). That highlights the intense eccentric load placed on the posterior rotator cuff muscles during the deceleration phase of throwing (DiGiovine et al., 1992). IR ROM has also been reported to decrease immediately after intense bouts of throwing (60 baseball pitches) and not return to baseline value until four days later. The underlying mechanism has been reported to be an increase in the infraspinatus muscle pennation angle, indicating increased infraspinatus sarcomere stiffness (Mirabito et al., 2022). These posterior shoulder soft tissue changes have been associated with changes in glenohumeral (GH) arthrokinematics, notably an increase in superior and anterior translation of the humeral head on the glenoid fossa during shoulder flexion and ER (Harryman et al., 1990; Huffman et al., 2006). The altered GH arthrokinematics have been proposed to cause internal impingement, a common shoulder pathology among overhead throwers, described as increased contact between the greater humeral tuberosity and the articular surface of the rotator cuff tendons during the late cocking phase of throwing, when the shoulder is positioned in abduction and maximal ER (Corpus et al., 2016). A systematic review, looking at the effectiveness of stretching showed it to be effective in reducing GIRD in overhead athletes (Mine et al., 2017), indicating the underlying mechanisms to truly be changes in GH soft tissue stiffness.

Scapular dyskinesis, an alteration in normal scapular kinematics and a proposed risk factor for shoulder problems in handball (Asker et al., 2020; Clarsen et al., 2014; Moller et al., 2017), has also been associated with internal impingement. Although, the role of scapular dyskinesis in the development of shoulder pain among the non-athletic population has been debated (Salamh, 2023), the evidence suggests that it can play a considerable role in shoulder problems among overhead throwing athletes due to the extensive use of the arms in an elevated position (Burn et al., 2016; Mihata et al., 2012). According to Mihata et al. (2012), reduced scapular upward and increased scapular IR during the late cocking phase of throwing, resulted in a significant increase in contact pressure between the greater humeral tuberosity and the posterior/superior glenoid, causing an increase in pressure on the rotator cuff tendons. These results indicate the importance of adequate strength and endurance in the scapulothoracic muscles, responsible for maintaining an optimal position of the scapula during throwing with respect to the upper arm (Bencke et al., 2018).

Due to the heavy eccentric load placed on the posterior shoulder during the deceleration of throwing (DiGiovine et al., 1992) and reduced ER strength being repeatedly described as a risk factor (Achenbach et al., 2020; Asker et al., 2020; Clarsen et al., 2014; Moller et al., 2017), reference values of 0.89 (male) and of 1.12 (female) for the ER/IR isometric strength ratio have been reported for handball players (Cools et al., 2016). ER strength has been reported to decrease immediately after throwing and not return to baseline until three days later (Mirabito et al., 2022). Such a drop can increase the chances of the

ER/IR strength ratio dropping below the known reference values for athletes who are under heavy throwing load and possibly increasing their risk of developing a shoulder problem. Looking at the athlete´s risk of developing a shoulder problem from a broader perspective is therefore critical.

1.3 Load management

The relationship between the athlete´s physical capacity and exposure to load in the form of sports participation is very important for injury risk management (Schwank et al., 2022). Load management has gained significant popularity following Tim Gabbett´s published work on the "Acute vs chronic workload ratio" (ACWR) (Gabbett, 2016). The ACWR represents the ratio of physical load for the previous seven days (acute) compared to the previous 28 days (chronic). It has been described as "best practice predictor of training-related injuries" and to be effective in predicting injuries in elite rugby players (Hulin et al., 2016). However, the acclaimed relationship between the ACWR and health problems has been criticized. Dalen-Lorentsen et al. (2021) pointed out that no two studies investigating this relationship have used the same methodological approach and no consensus exists on how this relationship should be calculated and analysed. In their study, Dalen-Lorentsen et al. analysed 108 different methodological combinations and concluded that the relationship between the ACWR and health problems is affected by the methodological approach used for data analysis. An example is the definition of a health problem, as the broadest definition of a health problem showed a much larger effect on the number of significant associations between the ACWR and health problems, compared to the narrowest one. Further, different definitions of the chronic period revealed different results, as the 28 days definition showed 50% more significant association compared to a shorter chronic period of 21 days. This highlights the importance of standardization of methodological approaches when investigating the effect of load management on injury risk.

Another way to measure risk factors relates to participation (e.g. increase in sports participation load) and physical factors (non-participation related) (e.g. reduced ER shoulder strength) (Moller et al., 2017). Moller et al. argued that only looking at the non-participation-related risk factors would be an oversimplification as injuries often occur because of an interaction between the load players are exposed to and their physical characteristics like strength. Their study showed that when youth handball players were exposed to >60% increase in weekly load, the injury rate rose significantly more than when the weekly load was increased by <20%. Importantly, the same study showed greater vulnerability to shoulder injury in players with reduced ER strength and scapular dyskinesis when the weekly handball load was increased by 20-60%, compared to players with "normal shoulder characteristics". These findings are in line with results from Hulin et al. (2016), indicating that athletes who are under high chronic load might be more resistant to injuries when exposed to moderate-low through moderate-high ACWR (0.85-1.35) but less resistant to injuries when exposed to extremely high spikes in acute load.

The results of these studies indicate that injuries likely occur due to a complex interaction between many different factors, modifiable and non-modifiable, and that just focusing on increasing the athlete´s physical capacity to tolerate more load might not be enough. Careful consideration of load management may be of even greater importance for injury management, as an inappropriate increase in training load is likely to blame for a large majority of non-contact soft tissue injuries in the athletic population (Gabbett, 2016).

The application of load can be registered both in the form of an external load (e.g. number of shots or minutes played per game) and an internal load (e.g. perceived experience of physical load). Studies have shown an increase in both types of loads to be associated with injuries (Fleisig et al., 2011; Gabbett, 2004). Baseball pitchers exposed to high external load (more than 100 innings per calendar year) were shown to be at significantly higher risk of suffering a serious shoulder and elbow injury compared to those who threw less than 100 innings (Fleisig et al., 2011). Similarly, an increase in internal load of rugby players (training intensity - measured with the modified rate of perceived exertion (RPE) scale) was associated with increased incidence of injuries (Gabbett, 2004). However, the best way to monitor shoulder specific load in overhead athletes is debated (Schwank et al., 2022). For example, the practicality of documenting external shoulder load can vary greatly between different throwing sports, from being relatively simple in a structured sport like baseball to very challenging in a chaotic collision and throwing sport like handball, where players are exposed to both intensive but fluctuating throwing and collision load. No consensus is available on whether external or internal load shoulder load measurements are considered more important for risk and management of shoulder problems among overhead athletes. However, the use of a self-reported measure to quantify players internal shoulder load in a sport like handball has been recommended (Schwank et al., 2022). That type of measure, where the athlete is asked to rate his perceived physiological experience following a training or a match on a scale from 0-10, can be defined as participation-related shoulder load (PSL).

1.4 The kinematics of throwing and the proximal-to-distal sequence

Overhead throwing is a complex movement involving the kinetic chain of the whole body. The kinetic chain has been described as a linkage of multiple body segments that create and transfer forces during activities such as throwing (Chu et al., 2016). The act of throwing in handball calls for forces to be transferred in a particular sequence from the lower extremities, through the pelvis and thorax and towards the upper arm, ending with the ball release. An efficient force transmission through the kinetic chain is based on the proximal-to-distal sequence principle, a vital part for efficient throwing performance in sports (Chu et al., 2016; Putnam, 1993). Description of the proximal-to-distal sequence is largely based on the summation of speed principle (Putnam, 1993). According to the principle, the end goal of reaching maximum speed in the distal segment relies on the initiation of movement in the proximal segments and that it continues in a specific sequence towards the more distal segments. The principle states that in a linked system of segments, a segment starts to move when its adjacent segment reaches its maximum speed and consequently the more distal segments reach a greater maximum speed than the previous ones.

The way a proximal segment in a linked system affects movement further up the kinetic chain has been explained by the effect of interactive moments (Putnam, 1993). Interactive moments occur when a movement of a proximal segment creates forces that influence a more distal segment. These forces are higher than what the distal segment could create on its own and the load, affecting that particular segment, is thereby reduced (Kibler, 2014; Putnam, 1993). The angular velocity of trunk rotation and shoulder internal rotation (IR) in a handball jump throw has been reported to be 756 °/s and 5039 °/s respectively (Wagner et al., 2010), highlighting the effect of interactive moments on the throwing kinematics. Another example is the forward acceleration of the forearm into elbow extension when throwing. While the elbow extensors are indeed active, the elbow extension joint moment created is too little to explain the extension movement of the elbow. This forward acceleration of the forearm into elbow extension is therefore primarily explained by the interactive moments produced by the acceleration of the shoulder and angular velocity of the upper arm (Putnam, 1993). Multiple studies have confirmed that handball players move through the proximal-to-distal sequence while throwing (Serrien & Baeyens, 2018; Wagner et al., 2010; Wagner et al., 2011, 2012). Two notable exceptions have, however, been described; peak leading leg hip flexion angular velocity occurs after the peak pelvis rotation (Wagner et al., 2010) and peak elbow extension occurs before the shoulder IR reaches its peak angular velocity (Serrien & Baeyens, 2018; Wagner et al., 2010).

Handball is a very dynamic sport where the key role of defensive players is to tackle opponents, stop the flow of the offensive game, and block shots at goal, so various throwing techniques have been described when the offence attempts to score (van den Tillaar et al., 2013; Wagner et al., 2011). Wagner et al. investigated the kinematic patterns and associated performance (ball velocity) of four different throwing techniques. The proximal-to-distal sequence was displayed during all four techniques, but greatest ball velocity was reached in a standing throw with a run-up, followed by a standing throw without run-up, jump throw and a pivot throw. The jump throw is the most common throwing technique in handball (Wagner H., 2008) but kinematic analysis of the jump throw is scarce. A distinctive feature of the jump throw is the lack of floor contact in the cocking and acceleration phases, which has been proposed to lead to a different movement strategy being utilized to transfer forces through the kinetic chain (Wagner et al., 2011) (Figure 1). In handball, the outfield positions consist of central, back, wing, and pivot players. The key difference regarding on-field throwing demands is that central and back players throw in general from a greater distance compared to wing and pivot players. Also, wing and pivot players pre-dominantly perform jump throws in contrast to central and back players who utilize both jump and standing throws. As a result, positional differences in throwing kinematics across different on-field positions likely exist, but the precise nature and extent of these differences have not been investigated before.

Figure 1 - The jump throw execution

Many other studies have indicated the importance of the kinetic chain function, particularly pelvis and trunk rotation, for various sport performance (Callaway et al., 2012; Dahl & van den Tillaar, 2021; Oliver & Keeley, 2010; van den Tillaar et al., 2013; Wagner et al., 2010; Wagner et al., 2011). Trunk rotation exercises have been shown to increase ball velocity for female handball players with the change specially attributed to increased angular velocity of the trunk (Dahl & van den Tillaar, 2021), indicating the importance of powerful trunk rotation for throwing performance. Oliver et al. (2010) showed a positive association between gluteal muscle activity and pelvis rotation during a pitching motion in baseball. Further, golfers with a low handicap were reported to have a significantly higher pelvis rotation angular velocity during the golf swing and significantly higher gluteus maximus and medius strength compared to high handicap golfers (Callaway et al., 2012). Kibler´s (1995) biomechanical analysis of the tennis serve showed that 51% of the total energy production originates from the lower extremities and the trunk, while only 13% was generated at the shoulder. Such results further support the importance of the kinetic chain for various overhead sports performance.

1.4.1 Sex-dependent throwing kinematics

Two studies have examined sex-dependent differences in throwing kinematics among handball players (Serrien et al., 2015; van den Tillaar & Cabri, 2012). Van den Tillaar et al. (2012) reported males to have a significantly higher ball velocity during a standing throw without a run-up. However, no differences in peak angular velocity were found for any of the segments measured but peak angular velocity of the trunk lateral tilt was found to occur significantly closer to ball release for male players compared to females. The authors therefore concluded that the sex-dependent difference in ball velocity was in large part due to greater height and muscle mass of male participants. In contrast, during a standing throw with a run-up, several sex-dependent differences were found for peak angular velocity and timing of peak angular velocity (Serrien et al., 2015). Female players displayed a larger shoulder ER angle during the cocking phase compared to male players and a significantly slower trunk rotation angular velocity during the preparation phase (Serrien et al., 2015). Female players further demonstrated a different movement pattern than males during throwing as they reached peak trunk flexion, pelvis lateral and backward tilting angular velocity earlier, relative to ball release. Those findings are in line with a part of the results from van den Tillaar et al. (2012), showing the peak trunk lateral tilt angular velocity to occur significantly closer to ball release for male players. Such a timing variation might influence the proximal-to-distal energy transfer since increased ball velocity has been associated with the peak pelvis rotation angular velocity being reached closer to ball release (van den Tillaar et al., 2013).

1.5 The suboptimal kinetic chain and its influence on the throwing shoulder

A number of studies have indicated that suboptimal use of the kinetic chain while throwing and/or deficits in the proximal segments, like limited mobility or reduced strength and power, increases the load on the more distal segments (Chu et al., 2016; Kibler, 2014; Kibler et al., 2013; Manzi et al., 2021; Oyama et al., 2014; Takagi et al., 2014). A cross-sectional study by Oyama et al. (2014) on baseball pitchers, showed that improper trunk rotation sequence (defined as reaching peak pelvis rotation angular velocity after reaching peak trunk rotation angular velocity) was associated with larger shoulder external rotation angle and shoulder joint forces. Manzi et al. (2021) termed that delayed peak pelvis rotation angular velocity as "discordant trunk rotation sequence" and showed that baseball pitchers who displayed such a sequence compensated by increasing their maximum shoulder ER angle and the horizontal abduction angle at maximum ER (MER). Further, increased shoulder distraction forces were displayed among the "discordant trunk rotation sequence" group. Results of another study on baseball pitchers showed that larger horizontal abduction angles at MER were associated with larger anterior shear forces in the throwing shoulder (Takagi et al., 2014). In combination, the results of these studies highlight the importance of adequate function of the kinetic chain and show how suboptimal proximal mechanics can be compensated for by the shoulder with subsequent increase in soft tissue stress. In a sport like handball, where the likelihood of scoring a goal often relies on the athlete´s ability to surprise the opponent and throw the ball as quickly as possible, the importance of efficient proximal mechanics is therefore vital. If a so-called "energy leak" is evident in that proximal power generation, a distal segment, like the shoulder, will need to move through a larger range of motion to reach necessary ball velocity and potentially predispose those players to shoulder problems.

Previous kinematics studies have all been limited by their cross-sectional design and recent prospective studies, looking at possible risk factors for shoulder problems among handball players, have primarily looked at local factors limited to the shoulder girdle

(Achenbach et al., 2020; Andersson et al., 2018; Asker et al., 2020; Clarsen et al., 2014; Moller et al., 2017). No prospective study has investigated possible effects of strength deficits in the kinetic chain on prevalence and severity of shoulder problems among handball players. Also, despite the jump throw being reported to be the most common handball throwing technique throw in competitive matches (73-75%) (Wagner H., 2008) and unique due to the lack of floor contact for the acceleration phase, very few studies have done a kinematic analysis of the jump throw. Assessment of the proximal segments´ contribution to important shoulder kinematic variables (e.g. IR angular velocity and ER/horizontal abduction ROM) in a jump throw is lacking, as is investigating potential difference in throwing kinematics between different playing positions. Knowledge in both areas is important as it might influence the focus and specialization in strength and power training in handball. The known importance of load management for the development of sport injuries and the lack of consensus on the most optimal type of load measurements in throwing athletes, also highlights the necessity of investigating which type of load measurements are most suitable for capturing and monitoring shoulder load in handball.

These missing links in the literature led to the development of this PhD project.

2 Aims

The first aim of this thesis was to assess the association between the pre-season kinetic chain strength and power among handball players, and the prevalence and severity of shoulder problems throughout the ensuing season. The second aim was to perform a kinematic 3D motion analysis of the jump throw to assess the proximal-to-distal sequence, identify correlations between proximal and distal segments´ kinematics during a jump throw, quantify the proximal segments' contribution to the shoulder kinematics, and highlight any differences in throwing kinematics between different playing positions. The third aim was to compare the usefulness of two different methods to measure shoulder specific load in handball by analysing their association with severity of shoulder problems and how pre-season kinetic chain strength and power influenced the strength of any association between shoulder load and the severity of shoulder problems.

2.1 Specific aims and hypotheses

2.1.1 Paper I

The aim of paper I was to assess the association between pre-season kinetic chain strength and power and shoulder problems over a course of a regular season in male handball players. Also, to assess the association between shoulder load (measured via internal, or self-reported participation-related shoulder load (PSL)) and the severity of shoulder problems and the influence of pre-season kinetic chain strength and power on any association between internal shoulder load and severity of shoulder problems.

The following hypotheses were tested:

1. A negative association would be seen between pre-season kinetic chain strength and power and shoulder problems for male handball players when followed through a regular season.
2. A positive association would be seen between PSL and severity of shoulder problems.
3. The magnitude of pre-season strength and power would influence the strength of the association between the magnitude of PSL and severity of shoulder problems, i.e. that greater strength and power would serve to weaken the association between the magnitude of PSL and severity of shoulder problems.

2.1.2 Paper II

The aim of paper II was to assess the association between pre-season kinetic chain strength and power and shoulder problems over a course of a regular season in female handball players. Also, to assess the degree to which pre-season strength and power influenced any association between shoulder load (measured as the internal PSL, as in Paper I, or as an external shoulder load based on documented number of shots in competition) and severity of shoulder problems.

The following hypotheses were tested:

1. A negative association would be seen between pre-season kinetic chain strength and power and shoulder problems for female handball players when followed through a regular season.
2. A positive association would be seen between shoulder load and severity of shoulder problems and that self-reported PSL (internal shoulder load) would show a more consistent association with the severity of shoulder problems compared to external shoulder load.
3. Magnitude of pre-season strength and power would influence the strength of the association between the magnitude of shoulder load and severity of shoulder problems.

2.1.3 Paper III

The aims of paper III were to do a kinematic 3D motional analysis of the jump throw, analyse the proximal-to-distal sequence and identify the correlation between proximal and distal segments´ kinematics, and to quantify the contribution of the proximal segments' kinematics to the IR angular velocity of the shoulder. Also, to compare the jump throw kinematics (°/s, ROM excursion and peak angles) between different playing positions.

The following hypotheses were tested:

1. Handball players would follow the proximal-to-distal sequence during a jump throw, but central/back players would demonstrate higher angular velocity, larger ROM excursion and peak angles of the hip, pelvis, thorax, elbow and shoulder compared to wing/pivot players due to different on-field demands.
2. A positive correlation would generally be demonstrated between the proximal and distal segments' peak angular velocity. However, reduced pelvis rotation kinematics would be correlated with a larger shoulder ER angle and a larger horizontal abduction angle at MER.
3. A substantial proportion of variance in shoulder IR angular velocity would be explained by hip, pelvis and thorax kinematics.

3 Materials and Methods

In this chapter, the methodology applied in this thesis will be described. The conduct of the project was approved by the National Bioethics Committee (VSN-22-084; VSN-22-084-V2).

3.1 Study design and participants

3.1.1 Paper I and III

In large, the same cohort of participants was used for paper I (a prospective study) and III (a cross-sectional study). Seven handball clubs from the Icelandic male top division were approached during the summer of 2022 and all outfield players over the age of 18, irrespective of their previous or current history of shoulder problems, were offered the opportunity to participate. Forty-eight players accepted the offer and showed up for the first part of the pre-season data collection in August and September 2022 at the Research Center of Rehabilitation and Movement Science, Department of Physical Therapy, University of Iceland. The first part included strength and power measurements where measurements for peak lower body strength, peak isometric shoulder ER and IR rotation strength and peak trunk rotation power (TRP) were conducted. The second part included a jump throw 3D kinematic motion analysis. Players who were away from normal training and competition due to injuries at the time of the data collection were excluded from participation. No other exclusion criteria were used. Approximately three weeks passed between the first and the second part of the data collection with 48 players showing up for the first part (paper I) and 42 for the second part (paper III). All participants provided written informed consent prior to participation.

3.1.2 Paper II

Paper II was a prospective study where participants were recruited from 6 clubs of the Icelandic female top division during the summer of 2023. All outfield players over the age of 18 were offered the opportunity to participate. Thirty-three players accepted and showed up for pre-season data collection in August and September 2023. The data collection took place at the Research Center of Rehabilitation and Movement Science, Department of Physical Therapy, University of Iceland and included a single session of the same pre-season strength and power measurement protocol as described for Paper I. The same exclusion criteria used for paper I and III were applied for paper II and all participants provided written informed consent prior to participation.

3.2 Isometric mid-thigh pull (Paper I and II)

For paper I and II, the peak lower body strength was measured with the Isometric mid-thigh pull (IMTP), a well-established and reliable test for lower body peak force measurements (Brady et al., 2020). Peak force of the IMTP has been shown to correlate highly with one repetition maximum in squat and deadlift, making the IMTP appropriate and convenient test for measuring lower body strength in the laboratory settings (De Witt et al., 2018; Wang et al., 2016).

Prior to testing, participants finished a standardized warm up and got three familiarization trials (at 50%, 75% and 90% subjective effort). During testing, knee and hip positions in the sagittal plane were standardized (between 125-145° and 140-145° respectively) as recommended by Comfort et al. (2019). Participants held a 20 kg weightlifting bar in a fixed position with their hands strapped to the bar with weightlifting straps to minimize the effect of their grip strength, while positioned on a force plate (AMTI, Watertown, Massachusetts, USA) sampling at 100 Hz to measure the vertical component of the ground reaction force (Figure 2). During each trial, the participants received verbal encouragement and were instructed, on cue, to push as hard and as fast as possible down into the force plate and maintain it for at least three seconds. Three trials were performed, and in cases where peak force (PF) values increased between the second and third trial, extra trials were conducted until the PF values differed by less than 250 N (Comfort et al., 2019). Data from all trials included the participant ´s body weight and the trials with the highest absolute PF value were used for data analysis.

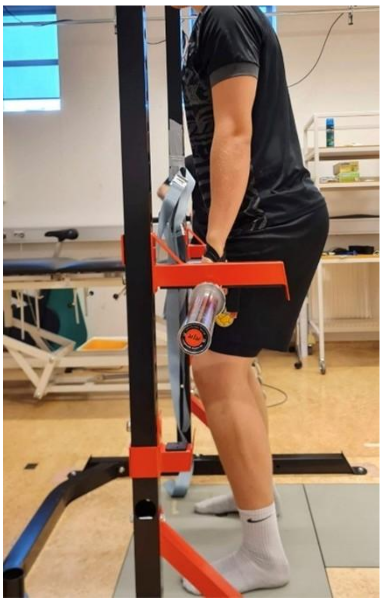

Figure 2 - Isometric mid-thigh pull testing

3.3 Isometric shoulder rotation strength (Paper I and II)

For paper I and II, the isometric shoulder ER and IR rotation strength of the throwing arm was measured with a fixed handheld dynamometer (Lafayette Instruments, Lafayette, Indiana, USA), using a protocol previously used in handball research and shown to have an excellent test-retest reliability (ICC 3.1 = 0.99) (Liaghat et al., 2020; Moller et al., 2017). The participants were placed in a supine position with the shoulder in 90° abduction and 0° rotation (Figure 3). To maintain the upper arm in the horizontal plane, a towel was placed underneath the distal end of the humerus. Prior to testing, participants finished a standardized warm up (Fredriksen et al., 2020) and got one familiarization trial (at 50% subjective effort). Participants were instructed, on cue, to push as hard as possible into the dynamometer and maintain it for a duration of three seconds. While testing they were instructed to keep their head, legs, torso, upper arm and elbow still to avoid any substitution movements. Stabilization was provided to the handheld dynamometer and to the upper arm by the examiner and participants got verbal encouragement during each trial. The average values from the three trials were used for data analysis (Liaghat et al., 2020). The pre-season ER/IR strength ratio was calculated by dividing the ER strength by the IR strength.

Figure 3 - Isometric shoulder external rotation testing

3.4 Trunk rotation power (Paper I and II)

For paper I and II, trunk rotation power (TRP) was measured with a pulley machine, with the participants in a seated position on a treatment plinth, keeping hips and knees at 90° flexion and feet flat on the floor (Andre et al., 2012). A non-slip mat was placed under the participants´ feet and buttocks to prevent any sliding on the floor or on the plinth.

Participants were instructed to keep the elbows fully extended in front of the body at shoulder height, the trunk in an upright position, feet firmly on the ground and to avoid all side bending motion, while rotating 5% of their body weight (BW) through 180° as fast as possible (Figure 4). Prior to testing, the participants completed a standardized warm-up and completed two familiarization trials (at 75% and 90% subjective effort). Only left-side rotation was measured for right-handed players and right-side rotation for left-handed players. The acceleration of the weight was measured using inertial sensors (Movella dot, Henderson, Nevada, USA), placed on the top of the weights in the pulley machine and raw data were collected through the Movella dot app (Movella dot, Henderson, Nevada, USA). The acceleration values were then converted to power in Microsoft Excel (2024) using the formula: $W=(a+g)*t*F$ where W=watt, a=acceleration, g=gravity, t=time, and F=force (representing the weight of the pulley). As seen by the time factor, the peak power value used for data analysis represented the total power produced throughout the whole rotation movement. This was done in an attempt to capture the dynamic nature of the trunk rotation used during throwing.

Three trials were performed and the trials with the highest absolute power value were used for data analysis. The reliability of the original version of the test was assessed by Andre et al, with participants rotating 9%, 12% and 15% of BW (Andre et al., 2012), compared to 5% of bodyweight used in paper I and II. Therefore, a new reliability analysis was done prior to starting data collection. Fourteen physiotherapy students were recruited, and each participant was measured twice, with 24-48 hours in between measurements, to determine the test-retest reliability. The results showed good reliability (mean: 28.0 W vs. 31.7 W; range 14.9 - 52.3 vs. 14.3 - 63.5), with an ICC (3,3) value of 0.874. The standard error of measurement (SEM) was 5.17 W, the coefficient of variation (CV) was 17%, and the minimal detectable difference using the 90% confidence level (MDD_{90}) of 12.03. Andre et al. (2012) reported slightly higher reliability of the original version (ICC 0.97, 0.94, and 0.95 for 9%, 12%, and 15% of BW, respectively) although they did not report SEM, CV or MDD_{90}.

Figure 4 - Seated trunk rotation power testing

3.5 Oslo Sports Trauma Research Center Overuse Injury Questionnaire (Paper I and II)

After the pre-season data collections, participants in paper I and II were followed through a whole regular season (31 weeks for paper I and 29 weeks for paper II) where information about the prevalence and severity of shoulder problems in the throwing arm was documented weekly. Self-reported data were collected and managed using REDCap (Nashville, Tennessee, USA) electronic data capture tools hosted at University of Iceland, with an Icelandic version of the Oslo Sports Trauma Research Center Overuse Injury Questionnaire (OSTRC-O2) (Clarsen et al., 2020) being emailed to all participants once a week. An automatic reminder was sent to non-responders after two and four days. If the participants had not answered the OSTRC-02 for three consecutive weeks, they were contacted and information gathered about possible reasons.

The OSTRC-O2 was originally designed to document the extent of overuse problems in sports in a more precise way than had been done before (Clarsen et al., 2013) and has since been widely used in handball-related research (Aasheim et al., 2018; Andersson et al., 2017, 2018; Asker et al., 2020; Clarsen et al., 2014; Rafnsson et al., 2021). Previous methods used for injury documentation in sports medicine were believed to have underestimated the real burden of overuse problems by only using time-loss definition of injuries (Clarsen et al., 2013). Therefore, the fact that many athletes continue to train and compete despite being symptomatic has been largely ignored. The questionnaire asked participants about shoulder problems in their throwing shoulder referring to any pain, ache, stiffness, clicking/catching, swelling, instability/giving way, locking, or other complaints related to the dominant shoulder. It included four questions asking whether shoulder problems had affected participation, training/competition, or performance, and whether participants had experienced any handball-related pain in the dominant shoulder during the previous seven days. The questionnaire answers thereby provide information about possible modification in participation and performance because of an overuse problem, which better captures the real extent of overuse problems compared to the previously used time-loss definitions.

Each question offers four response options, scored as 0-8-17-25 points, 0 representing no problem and 25 maximum level (appendix A). The scores from each of these four questions were then summed to calculate a weekly severity score on the scale 0-100. The average OSTRC-O2 severity score for each participant was calculated by dividing the total score from all the questionnaires answered throughout the season by the number of times answered. The weekly group prevalence of shoulder problems was calculated by dividing the total number of times any participants reported any problem (anything but the minimum value in any of the four questions) with the total number of questionnaire respondents that same week. The individual prevalence of shoulder problems was calculated by dividing the total number of times each participant reported a problem (anything but the minimum value in any of the four questions) by the total number of that participants´ questionnaire responses. The group and individual prevalence of *substantial problems* was calculated in the same way, respectively, for shoulder problems that had caused moderate or severe reduction (score 17 or 25 on questions number 2 or 3 or both on the OSTRC-O2) in training/competition or performance or total inability to participate (score 25 on question number 1 on the OSTRC-O2) (Clarsen et al., 2020).

3.6 Shoulder load (Paper I and II)

In addition to the weekly OSTRC-O2, novel ways of documenting both internal (paper I and II) and external shoulder load (paper II) were applied. To document internal load, a question was added to the weekly questionnaire asking the participants to rate their weekly PSL using the modified Borg rate of perceived exertion scale (0-10 scale with specific description for each score) by answering the question "How hard was the recent week on your throwing arm?" (Schwank et al., 2022). The average PSL for each participant was calculated by dividing the total PSL score from all the questionnaires answered throughout the season by the number of questionnaires answered. As an attempt to objectively document the external load, information about the total number of shots taken by each participant in all league matches throughout the regular season were collected from performance data provided by HBStatz (www.hbstatz.is). HBStatz is an Icelandic handball analytics platform that serves as the official statistics provider for the Icelandic Handball Association and collects detailed, real-time match data from the top men's and women's divisions, using trained observers and strict quality control procedures.

3.7 Jump throw kinematic motion analysis (Paper III)

In paper III, a kinematic 3D motion capture and analysis of a jump throw was performed. The participants finished a standardized warmup including two minutes on a stationary bike, a set of shoulder ER and IR at 90° of abduction using a resistance band, 10 push-ups and two minutes of throwing drills. After the warmup, the participants made 3-5 practice jump throws to get familiar with the laboratory setting. For the data collection, each participant was instructed to do a 2-3 meter run up, where the last step was onto a force plate (AMTI, Watertown, Massachusetts, USA) from which they pushed off and threw a ball (IHF size 3 with handball wax) towards a handball goal positioned approximately four meters away from the force plate. Participants were asked to perform the jump throw in a normal fashion, as they were used to during training. Three attempts were recorded for each participant and used for data analysis.

The motion capture was conducted using a 12-camera system (Qualisys, Gothenburg, Sweden) sampling at 700 Hz. Forty reflective markers were used to define and track the segments of interest: Left and right thigh, pelvis, thorax, upper arm and forearm of the throwing arm. Shanks and feet were not defined as knee and ankle kinematics were not analyzed because their contribution is likely minimal in the absence of floor contact. The forearm was defined for the purpose of identifying minimal elbow flexion (end of throwing motion). The hand was not defined as the contribution of wrist kinematics was not examined, due to the focus on shoulder kinematics. After capturing a static trial eight anatomical markers were removed, leaving clusters of three to five markers to track each segment (Table 1), (Figure 5). The jump throw motion was analysed between the moment of toe off from the force plate to the point of minimal elbow flexion in the throwing arm, which served as a proxy for ball release (Wagner et al., 2011). The raw marker data were digitized within the Qualisys Track Manager software and then exported and processed further within Visual-3D (HAS motion, Detroit, Michigan, USA). Computed data was filtered with the Butterworth lowpass filter with a cut-off frequency of 12 Hz. Hip and thorax angles were calculated with respect to the pelvis, and the pelvis angles were calculated with respect to the global reference system of the lab. Shoulder angles were defined as the angle between the upper arm and the thorax, and the elbow angle was defined as the movement of the forearm with respect to the upper arm. ROM excursion was defined as the difference between peak angles of opposing movements (flexion -> extension, external -> internal rotation and horizontal abduction -> horizontal adduction) during the throwing motion. Thorax external rotation was defined as rotation towards the throwing arm. The leg used for push-off was defined as the leading leg and the opposing leg was defined as the trailing leg. Negative kinematic values for left-handed players were converted to positive values before data analysis, so all data were analysed as if from right-handed players. The timing of peak angular velocity was identified and normalized to the duration of the defined throwing motion. The Cardan sequence X-Y-Z was applied to all segments except for the shoulder ER/IR ROM, where the Cardan sequence Z-Y-Z was applied.

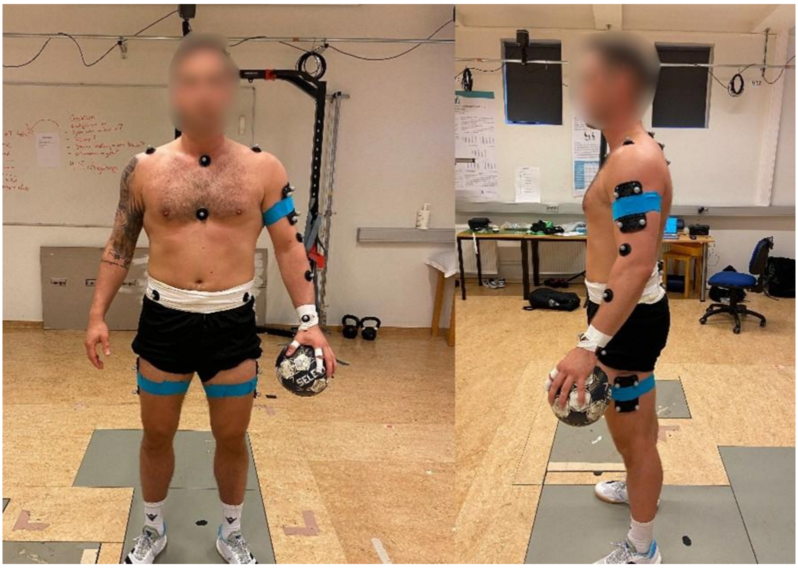

Figure 5 - Location of tracking markers

Table 1 - Landmark and number of reflective markers used.

Landmarks	Number of reflective markers
Thigh segment clusters (L&R)	2*4; tracking
Med/Lat femoral condyles (L&R)	4 - anatomical
Greater trochanter (L&R)	2 - anatomical
Anterior superior iliac spine (L&R)	2 - anatomical
Posterior superior iliac spine (L&R)	2 - tracking
Sacrum	1 - tracking
Iliac crest (L&R)	2 - anatomical
Sternum	1 – tracking
Xiphoid process	1 – tracking
Acromion (L&R)	2 – anatomical
T2	1 – tracking
T8	1 – tracking
Upper thorax	4 – tracking
Body of the humerus*	4 – tracking
Medial epicondyle of the humerus*	1 - tracking
Lateral epicondyle of the humerus*	1 – anatomical
Middle of the forearm*	1 – tracking
Distal radius*	1 – anatomical
Distal ulna*	1 – anatomical

3.8 Outcome measures

The outcome measures for each paper were as follows:

Paper I:

a) The association between the participants' pre-season kinetic chain strength and power and the OSTRC-O2 results (individual prevalence, individual prevalence of substantial shoulder problems and severity score).
b) The influence of the participants' pre-season kinetic chain strength and power on the association between the PSL and the OSTRC-O2 severity score.

Paper II

a) The association between participants' pre-season kinetic chain strength and power and the OSTRC-O2 results (individual prevalence, individual prevalence of substantial shoulder problems and severity score).
b) The influence of participants' pre-season kinetic chain strength and power on the association between the PSL and the OSTRC-O2 severity score.
c) The influence of participants' pre-season kinetic chain strength and power on the association between the external load and the OSTRC-O2 severity score.

Paper III

a) Joint and segment ROM excursion, peak angles, magnitude and relative timing of the peak angular velocity within the defined duration of the throwing motion, comparing data of central/back players and wing/pivot players (*Proximal-to-distal sequence variables: Hip extension/flexion, pelvis rotation, thorax flexion/extension/rotation, elbow extension and shoulder IR. Additional ROM variables: Shoulder ER/IR and horizontal abduction/adduction*).
b) Correlation between the proximal and distal kinematic variables.
c) Proportion of variance in shoulder IR angular velocity explained by the proximal segments' kinematics.

3.9 Statistical and data analysis

All statistical analysis were done in Microsoft Excel (2024) and Jamovi statistical software (2025). For all papers, the Shapiro-Wilk test was used to check for normal distribution of the data. In paper I, the Spearman´s rho correlation coefficient was used to assess the association between the pre-season strength and power measurements and the OSTRC-O2 results. A mixed model ANOVA was used to assess the influence of each pre-season strength and power measurements and internal shoulder load on the severity of shoulder problems (main effects) and the interaction of those variables.

In paper II, the Spearman´s rho correlation coefficient was used to assess the association between pre-season strength and power measurements and a) OSTRC-O2 results and b) the external load. A mixed model ANOVA was used to assess the influence of each pre-season strength and power measurements and shoulder load on the severity of shoulder problems (main effects) and the interaction of those variables. Partial eta squared was calculated using the formula $\eta^2_p = t^2/(t^2+dft)$ to demonstrate the effect size of the mixed model ANOVA interactions (t^2 = The square of the *t*-statistic from the ANOVA interaction term (Jamovi); df_t = The degrees of freedom associated with the *t*-test).

In paper III, independent *t* tests and Mann-Whitney U tests were used to assess differences in the jump throw kinematic variables (°/s, ROM excursion and peak angle) between central/back players and wing/pivot players. Paired *t*-test and Wilcoxon signed rank tests were used to assess the relative timing of peak angular velocity between consecutive segments and the Pearson correlation coefficient/Spearman´s rho were used to analyse the correlation between the proximal and distal segments´ kinematics. A stepwise regression model, including all proximal variables with a significant correlation with shoulder IR angular velocity (dependent variable), was used to assess the contribution of the proximal segments´ kinematics to the shoulder kinematics.

Additional analysis was done (not included in the original manuscripts) where the correlation between the pre-season measurements and external load for male players from paper I was assessed with the Spearman´s rho. A mixed model ANOVA was used to assess the influence of sex on the association between the combined pre-season measurement from paper I and II (relative to body weight for the sake of comparison between male vs female) and the severity of shoulder problems. Also, a mixed model ANOVA was used to assess the influence of each pre-season measurements and external load on the severity of shoulder problems (main effects) and the interaction of those variables for male players from paper I. An *a-priori* power analysis was conducted, indicating a sample size of minimum 46 participants to achieve 80% power for a correlation value of 0.4 for the association between the pre-season strength and power measurements and the OSTRC-O2 results. The *p* value was set at 0.05 for all analyses. Correlation strength was interpreted for all papers as follows: 0-0.1 = negligible, 0.2-0.39 = weak, 0.4-0.69 = moderate, 0.7-0.89 = strong, and 0.9-1 = very strong (Schober et al., 2018).

4 Results

4.1 Paper I (males) and Paper II (females)

Due to similarities between paper I and II, results from both papers will be presented here for the purpose of highlighting commonalities and sex-dependent differences. A total of 48 male handball players were recruited in paper I. Two left the study right after the pre-season measurements, two dropped out due to injuries, one stopped playing handball and one was lost in follow-up. Data from 42 players (age 18 to 37) were therefore available for data analysis. In paper II, 33 female handball players were recruited. Two were lost in follow-up for unknown reasons, leaving data from 31 players (age 18 to 35) available for data analysis. Participants' demographics can be found in Table 2. No statistical differences were found regarding mean age and mean elite handball experience between male and female players.

Table 2 - Participants' demographics

Demographics	**Males (n = 42) mean (SD)/n**	**Females (n = 31) mean (SD)/n**
Age	24.3 (4.7)	23.5 (4.6)
Height (cm)	189 (7.0)	173 (5.8)
Weight (kg)	90.5 (10.2)	77 (8.0)
Elite handball experience (years)	7.1 (4.6)	7.5 (4.8)
Hand dominance (r/l)	27/15	27/4

SD = standard deviation, cm = centimeters, kg = kilograms, r = right, l = left, elite handball experience = number of years as a player in the first team squad.

4.1.1 Shoulder problems, internal and external load

Results based on the OSTRC-O2, the self-reported PSL (internal load), and documented number of shots on goal during competition (external load) for male and female handball players (paper I and II, respectively) can be found in Table 3. The difference in mean external load values of males vs females did not reach statistical significance (*p* = 0.087).

Table 3 - The average OSTRC-O2 response rate, group weekly prevalence of shoulder problems, and substantial shoulder problems, OSTRC-O2 severity score and internal/external load for male and female players.

	Males mean (95% CI)	**Females mean (95% CI)**
OSTRC - O2 response rate	87% (82.1 - 92.0)	88% (81.5 - 94.8)
Group weekly prevalence of shoulder problems	27% (19.8 - 35.2)	20% (17 - 22.5)
Group weekly prevalence of substantial shoulder problems	4% (1.7 - 7.8)	3.4% (2.2 - 4.6)
Severity score (0 - 100)	7.6 (5.3 - 9.8)	7.7 (3.8 - 11.7)
PSL (0 - 10)	4.1 (3.7 - 4.4)	3.9 (3.4 - 4.4)
External load	91 (88 - 94)	71 (47 - 95)

OSTRC-O2 = Oslo sports trauma research center overuse injury questionnaire, PSL = participation-related shoulder load, external load = number of shots taken per player in league matches during the regular season.

4.1.2 Pre-season strength and power - association with OSTRC-O2

The relative (normalized to body weight) pre-season strength and power results from males (paper I) and females (paper II) can be found in Table 4. For males, a weak negative correlation was found between the absolute pre-season ER strength and the individual prevalence of shoulder problems (r_s = -0.34, p = 0.029). No pre-season measurement had a statistically significant correlation with the severity score (r_s range: -0.22 to -0.11; *p* values range: 0.16 to 0.51) or the individual prevalence of substantial shoulder problems (r_s range: -0.01 to 0.12, *p* values range: 0.44 to 0.96).

For females, a moderate and positive correlation was found between the absolute pre-season IMTP and the individual prevalence of substantial shoulder problems (r_s = 0.40, *p* = 0.03). A weak positive correlation was found between absolute pre-season ER and IR strength and the severity score (r_s = 0.37, *p* = 0.04 for both), as well as between absolute ER strength and the individual prevalence of substantial shoulder problems (r_s = 0.38, p = 0.04).

Table 4 - Mean and 95% confidence intervals (CI) of relative pre-season strength and power measurements and ER/IR ratio from paper I (males) and II (females).

Measurements (unit)	**Males mean (95% CI)**	**Females mean (95% CI)**
ER (kg/BW) **	0.24 (0.22 – 0.25)	0.17 (0.16 – 0.18)
IR (kg/BW) **	0.26 (0.24 – 0.27)	0.18 (0.16 – 0.18)
IMTP (N/BW) **	36.6 (35.0 – 38.1)	31.5 (29.8 – 33.3)
TRP (W/BW) *	0.43 (0.40 – 0.47)	0.35 (0.32 – 0.39)
ER/IR ratio *	0.94 (0.88 – 1.0)	1.04 (0.99 – 1.09)

ER = external rotation, IR = internal rotation, IMTP = Isometric mid-thigh pull, TRP = trunk rotation power, kg = kilograms, N = Newton, W = watts, BW = body weight, * = $p < 0.05$, ** = $p < 0.001$. Note: IMTP values include participants' body weight.

4.1.3 Association between the PSL and the OSTRC-O2 severity score - the influence of pre-season strength and power

In all mixed model ANOVAs for the male participants, using the severity score as the dependent variable, a main effect was found for the self-reported PSL ($p < 0.001$), indicating that with higher PSL, a higher severity score was observed. A statistically significant interaction was found between the PSL and pre-season TRP in terms of their influence on the severity score ($r^2 = 0.39$, $p = 0.017$, $\eta^2_p = 0.005$). Players with pre-season TRP more than one SD below the group's mean showed a significantly stronger association between PSL and the severity score compared to players with greater pre-season TRP (Figure 6). An interaction, close to statistical significance, was also observed between the PSL and the pre-season IR strength with respect to the severity score, indicating that players with low pre-season IR strength reported higher severity scores as the PSL increased ($r^2 = 0.39$, $p = 0.05$, $\eta^2_p = 0.003$).

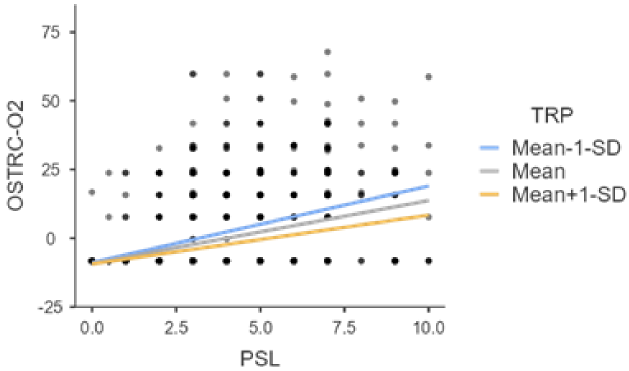

Figure 6 - The interaction between the PSL and TRP in terms of their influence on the OSTRC-02 severity score. PSL = participation-related shoulder load, TRP = trunk rotation power, OSTRC-O2 = Oslo sports trauma research center overuse injury questionnaire, SD = standard deviation.

For female players, as for males, in all mixed model ANOVAs using the severity score as the dependent variable, a main effect was found for the self-reported PSL (p < 0.001), indicating that with higher PSL, a higher severity score was observed. A statistically significant interaction was observed between PSL and pre-season TRP, IMTP, and ER strength in terms of their influence on the severity score (r^2 = 0.57, p = 0.001, η^2_p = 0.014; r^2 = 0.59, p = <0.001, η^2_p = 0.02; r^2 = 0.57 p = 0.01, η^2_p = 0.008, respectively). Conversely to the results seen for males, female players with pre-season TRP, IMTP, and ER strength more than one SD above the group's mean showed a significantly stronger positive association between PSL and the severity score than those with lower pre-season strength (Figure 7). No statistically significant interaction was found between PSL and pre-season IR strength with respect to the severity score, (r^2 = 0.57, p = 0.1, η^2_p = 0.003).

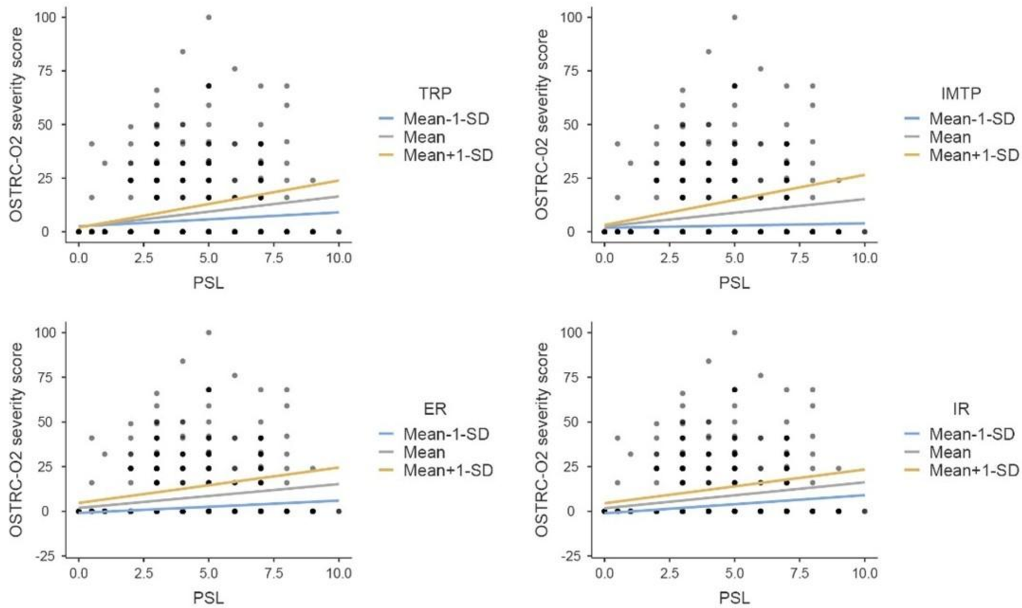

Figure 7 - The interaction between the PSL and TRP, IMTP, ER, and IR in terms of their influence on the OSTRC-02 severity score. PSL = Participation-related shoulder load, TRP = trunk rotation power, IMTP = isometric mid-thigh pull, ER = external rotation strength, IR = internal rotation strength, OSTRC-O2 = Oslo sports trauma research center overuse injury questionnaire, SD = standard deviation.

4.1.4 Association between external load and the OSTRC-O2 severity score - the influence of the pre-season strength and power

Data representing the external load were not included in paper I but are a part of this thesis. For male players, no main effect was found for the external load regarding its association with the OSTRC-O2 severity score. No interaction was found between any of the pre-season measurements and the external load in terms of their influence on the severity score (TRP $p = 0.59$; IMTP $p = 0.49$; ER $p = 0.92$; IR $p = 0.53$).

In contrast, for female players, a significant negative main effect was found for the external load regarding its association with the severity score ($p = 0.04$), indicating that higher number of shots was associated with lower severity score. However, that main effect was only found when the mixed model ANOVA included pre-season ER strength as a covariate. A significant interaction was found between the external load and ER strength regarding their influence on the severity score ($r^2 = 0.52$, $p = 0.04$, $\eta^2_p = 0.15$). Players with ER strength one SD below the group´s mean demonstrated a stronger negative association between external load and the severity score, compared to no association for players with ER strength one SD above the group´s mean (Figure 8).

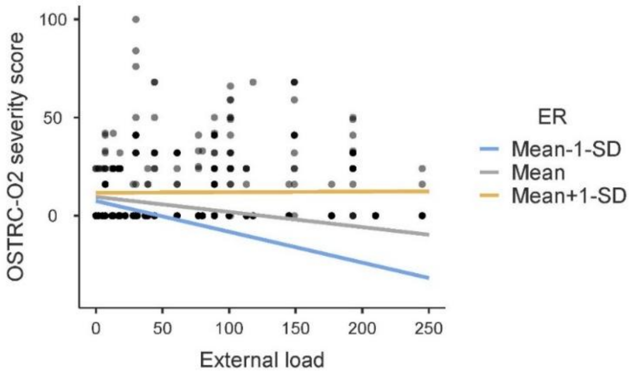

Figure 8 - The interaction between external load and pre-season ER strength in terms of their influence on the OSTRC-O2 severity score from paper II. ER = external rotation. OSTRC-O2 = Oslo sports trauma research center overuse injury questionnaire, external load = number of shots per player throughout the regular season.

4.1.5 Association between the pre-season strength and power and the external load experienced through the season

Due to the sex-related differences between results identified in paper I and II, additional analyses were done (not included in the original manuscripts). Correlation between the pre-season absolute measurements and the external load was assessed. Notably, the correlation coefficients indicate that female players demonstrated a stronger association between most pre-season strength and power measures and external load compared to male players (Table 5), where stronger players were likelier to take more shots at goal throughout the season.

Table 5 - Pearson´s/Spearman´s correlation coefficients for associations between the pre-season absolute measurements and the external load for male and female players.

Pre-season measurement	**External load (male)**	**External load (female)**
IR (kg)	0.38*	0.50*
ER (kg)	0.28	0.62**
IMTP (N)	0.33*	0.73**
TRP (P)	0.58**	0.54*

* = *p* > 0.05, ** = *p* > 0.001, IR = internal rotation, ER = external rotation, IMTP = Isometric mid-thigh pull, TRP = trunk rotation power, kg = kilograms, N = Newton, W = watts.

4.1.6 Association between pre-season strength and power and the OSTRC-O2 severity score - the influence of sex

Data from paper I and II were combined to enable the detection of sex-dependent differences regarding the association between relative pre-season strength and power (normalized to body weight) and the severity score (as the dependent variable). A significant main effect was found for relative pre-season ER and IR strength (p = 0.015, p = 0.043, respectively), indicating that, overall, increased relative ER and IR strength was associated with a higher severity score (Figure 9). No main effect was found for sex. However, a statistically significant interaction was found due to sex-dependent differences in the association between all of the pre-season strength and power measurements in terms of their influence on the severity score (ER r^2 = 0.47, p = 0.003; IR r^2 = 0.47, p = 0.012; IMTP r^2 = 0.47, p = 0.01; TPR r^2 = 0.47, p = 0.007). Whereas females showed a positive association between pre-season strength and power and the severity score, this was generally negative in male players (Figure 9).

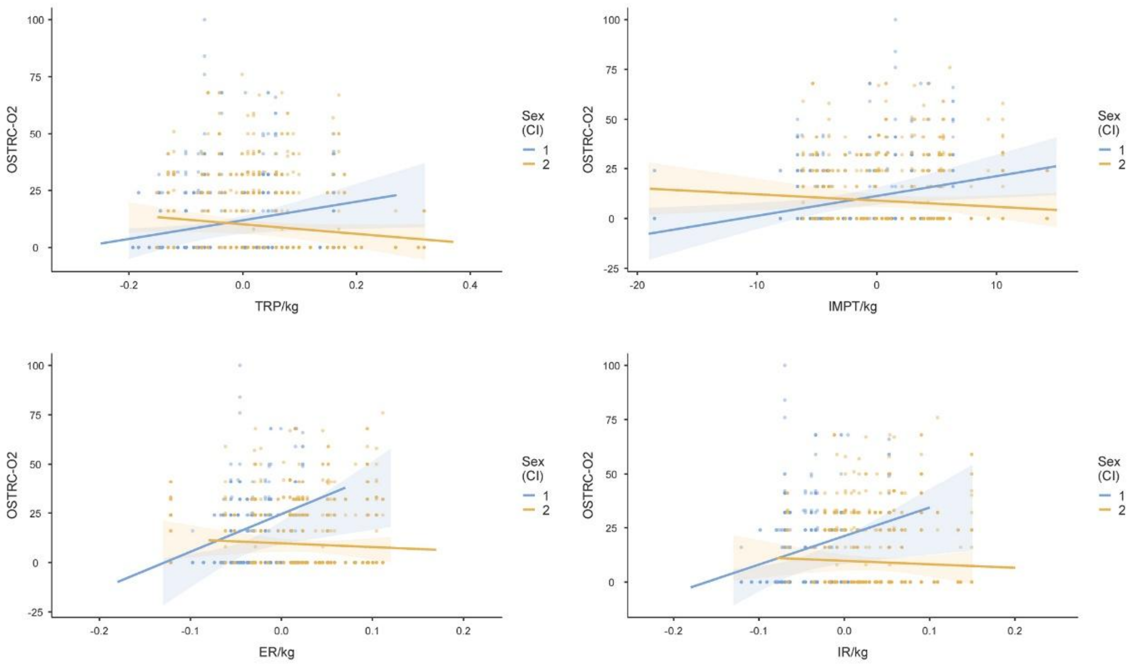

Figure 9 - The interaction between sex and the pre-season measurements in terms of their influence on the OSTRC-O2 severity score. OSTRC-O2 = Oslo sports trauma research center overuse injury questionnaire, TRP = trunk rotation power, IMTP = Isometric mid-thigh pull, ER = external rotation, IR = internal rotation, 1 = female, 2 = male.

4.2 Paper III

A total of 42 male handball players participated in paper III. One participant was not able to complete the data collection due to an injury, leaving data from 41 players available for data analysis. Twenty participants were central/back players and 21 were wing/pivot players. Their mean (SD) age, height and weight were 24.3 (4.7) years, 188 (6.3) cm and 89.1 (9.0) kg, respectively and they had on average seven years (4.7) experience as first team players. Central/back players were significantly taller (mean difference = 2.1 cm, p = 0.008) with no difference for average weight, age or first team experience between the groups.

Figure 10 shows the average proximal-to-distal sequence during the jump throw for all participants. The participants followed the proximal-to-distal sequence, except for the peak leading leg hip flexion angular velocity occurring after the peak pelvis rotation, and peak elbow extension occurring before peak shoulder IR. Peak shoulder IR angular velocity occurred after the pre-defined end of the throwing motion, explaining the above 100% value.

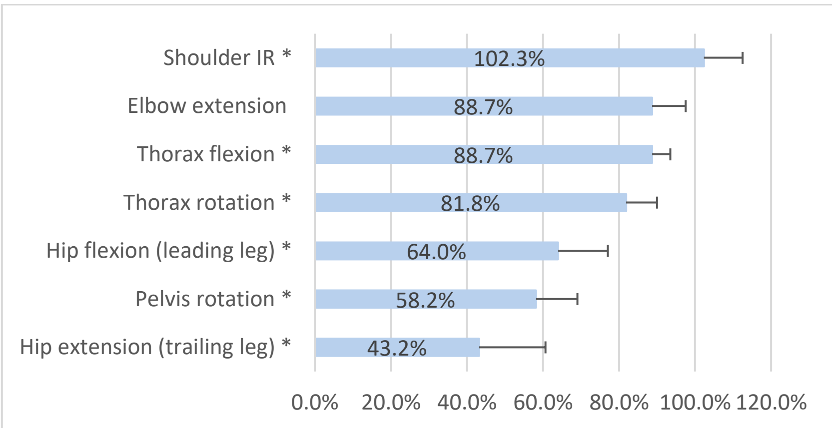

Figure 10 - The average proximal-to-distal sequence during a jump throw (all participants (Y-axis)). The relative timing of peak angular velocity as a percentage of total duration of the throwing motion (X-axis). IR = internal rotation, SD = standard deviation.*Timing of peak angular velocity significantly different than that of the segment below (p < 0.01). Due to multiple paired t tests/Wilcoxon signed rank test performed, significance level was set at p = 0.05/6 = 0.008.

Figures 11 and 12 show the proximal-to-distal sequence for each wing/pivot and central/back player, respectively. Both groups followed in general the same sequence as described above, with central/back players reaching peak angular velocity earlier for all segments/joints. Statistically significant between-group differences were found for the timing of peak angular velocity for hip extension of the trailing leg (p = 0.003), hip flexion of the leading leg (p = 0.004), elbow extension, and shoulder IR (p < 0.001 for both) (Table 6).

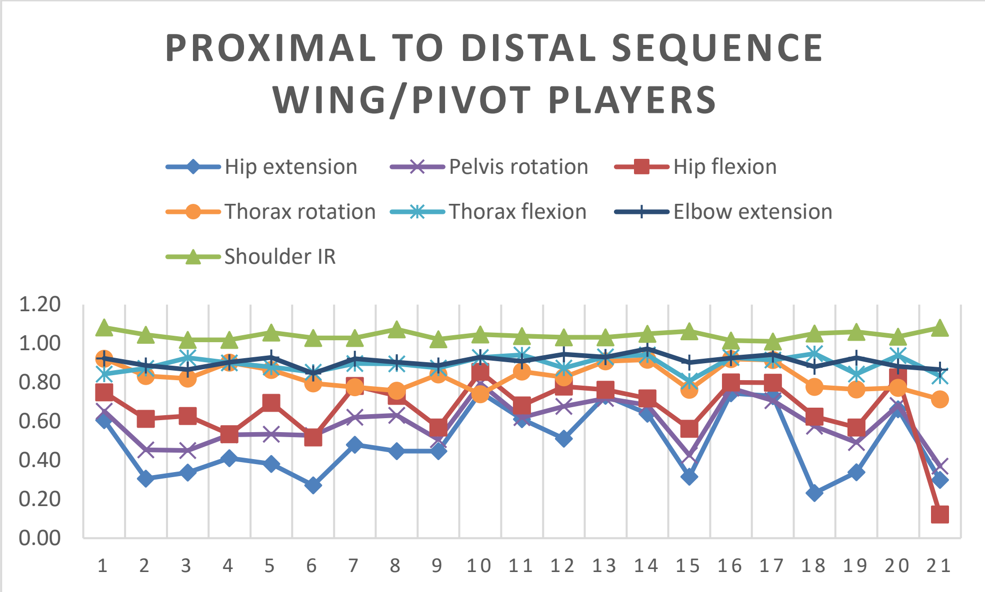

Figure 11 - Wing/pivot players - The average timing of the proximal-to-distal sequence during a jump throw. The relative timing of peak angular velocity as a percentage of total duration of the throwing motion (Y-axis) and each participant (X-axis).

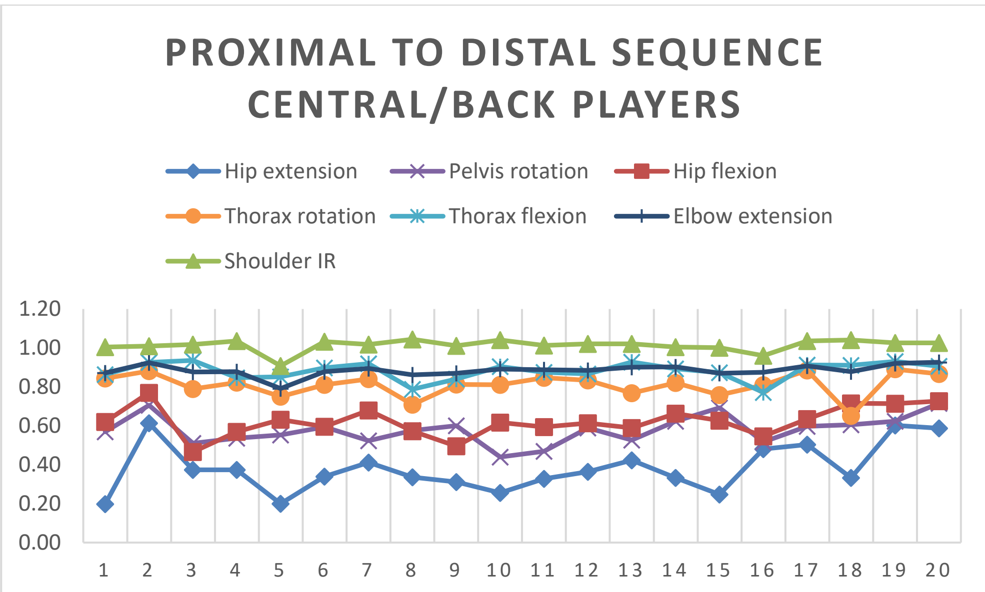

Figure 12 - Central/back players - The average timing of the proximal-to-distal sequence during a jump throw. The relative timing of peak angular velocity as a percentage of total duration of the throwing motion (Y-axis) and each participant (X-axis).

Table 6 - The relative timing of each joint/segments' peak angular velocity (mean and SD) as a percentage of the total duration of the defined throwing motion for each group.

Joint/Segment motion	**Central/back players (n = 20)**	**Wing/pivot players (n = 21)**
Hip extension[a] *	37.8 (13.3)	48.2 (19.3)
Pelvis rotation	57.6 (8.7)	58.7 (12.5)
Hip flexion[b] *	61.9 (8.0)	66.0 (16.2)
Thorax rotation	81.0 (7.4)	82.7 (8.8)
Thorax flexion	88.0 (4.8)	89.3 (4.7)
Elbow extension **	88.2 (3.0)	89.2 (1.2)
Shoulder IR **	100.0 (13.8)	105.0 (3.7)

* = $p < 0.05$, ** = $p < 0.001$, a = trailing leg, b = leading leg, IR = internal rotation.

4.2.1 Central/back vs wing/pivot players - Magnitude of players' jump throw kinematics

Tables 7, 8 and 9 display the kinematic differences (peak angular velocity, ROM excursion and peak angle) between the central/back and wing/pivot players. Central/back players displayed significantly higher peak angular velocity for all segments, except for thorax rotation (Table 7). They also displayed significantly larger ROM excursion for the leading leg hip flexion, pelvis rotation, thorax flexion and shoulder rotation (Table 8), and larger peak angles for leading leg hip flexion, shoulder ER and horizontal abduction (Table 9).

Table 7 - Mean (SD) peak joint/segmental angular velocity (°/s) during the throwing motion and mean (SE) for group differences.

Joint/segment (°/s)	All players (n=41)	Central/back players (n=20)	Wing/pivot players (n=21)	Mean (SE) difference
Hip extension[a]	566 (170)	607 (125)	529 (196)	78 (30) *
Pelvis rotation	420 (100)	447 (73)	395 (115)	52 (18) **
Hip flexion[b]	548 (138)	581 (89)	518 (167)	63 (25) *
Thorax rotation	301 (323)	338 (257)	267 (373)	71 (59)
Thorax flexion	488 (136)	555 (99)	426 (136)	129 (22) **
Elbow extension	760 (153)	801 (143)	722 (153)	79 (27) *
Shoulder IR	1816 (478)	2064 (309)	1587 (493)	477 (76) **

IR = internal rotation, * = $p < 0.05$, ** = $p < 0.001$, SE = standard error, °/s = degrees per second, a = trailing leg, b = leading leg.

Table 8 - Mean (SD) range of motion excursion (°) during the throwing motion and mean (SE) for group differences.

Joint/segment (direction of motion)	All players (n=41)	Central/back (n=20)	Wing/pivot (n=21)	Mean (SE) difference
Hip following leg[a] (flex -> ext)	72.7 (15.2)	71.2 (13.4.)	74.0 (16.6)	-2.9 (2.8)
Pelvis rotation	71.0 (14.9)	77.4 (11.6)	65.1 (15.3)	12.3 (2.5) **
Hip leading leg[b] (ext -> flex)	57.7 (10.3)	61.7 (8.51)	54.0 (10.4)	7.7 (1.8) **
Thorax (ER -> IR)	48.7 (11.3)	46.5 (8.3)	50.8 (13.2)	-4.3 (2.0)
Thorax (ext -> flex)	29.3 (8.7)	33.5 (8.0)	25.6 (8.0)	7.7 (1.6) **
Shoulder (ER -> IR)	40.7 (11.0)	44.2 (11.8)	37.4 (9.2)	7.9 (1.9) *
Shoulder (HABD -> HADD)	54.8 (17.2)	55.0 (14.4)	54.7 (19.8)	0.3 (3.2)

Flex = flexion, ext = extension, IR = internal rotation, ER = external rotation, HABD = horizontal abduction, HADD = horizontal adduction * = $p < 0.05$, ** = $p < 0.001$, SE = standard error, ROM = range of motion, a = follow leg, b = lead leg.

Table 9 - Peak joint angles (°) during the throwing motion: Mean (SD) for each group and mean (SE) for group differences.

Segment	All players (n=41)	Central/back (n=20)	Wing/pivot (n=21)	Mean (SE) difference
Hip extension[a]	5.6 (11.5)	6.7 (7.6)	4.5 (14.1)	2.2 (2.1)
Hip flexion[b]	58.9 (9.6)	62.2 (7.8)	55.8 (10.1)	6.4 (1.7) **
Thorax ER	33.0 (11.5)	32.1 (15.3)	33.9 (6.4)	-1.8 (2.2)
Thorax extension	37.7 (10.2)	36.5 (9.4)	38.7 (10.8)	-2.2 (1.9)
Shoulder ER	105 (8.6)	107.2 (10.0)	103.0 (6.4)	4.2 (1.5) **
Shoulder HABD	36.7 (10.7)	39.6 (10.1)	34.1 (10.6)	5.5 (1.9) *

IR = internal rotation, ER = external rotation, HABD = horizontal abduction, * = $p < 0.05$, ** = $p < 0.001$, SD = standard deviation, ROM = range of motion, a = following leg, b = leading leg.

4.2.2 The correlation between proximal and distal variables

Table 10 shows the correlation coefficients for the associations between segments/joints' peak angular velocity relevant to the proximal-to-distal sequence.

Table 10 - Pearson´s/Spearmans´ correlation between the mean peak angular velocity (°/s) during the throwing motion.

Joint/ segment	Hip ext	Pelvis rotation	Hip flexion	Thorax rotation	Thorax flexion	Elbow ext	Shoulder IR
Hip ext[a]		0.74**	0.37**	0.001	0.31**	-0.01	0.43*
Pelvis rotation			0.49**	0.12	0.32**	-0.07	0.56**
Hip flexion[b]				0.12	0.35**	0.02	0.15
Thorax rotation					0.06	0.30*	0.02
Thorax flexion						0.25*	0.37*
Elbow ext							0.11
Shoulder IR							

Ext = extension, IR = internal rotation, * = $p < 0.01$, ** = $p < 0.001$, a = trailing leg, b = leading leg.

The correlation between peak shoulder IR angular velocity and other proximal kinematic variables was also assessed and the results showed a positive correlation between shoulder IR angular velocity and the ROM excursion of the leading leg's hip flexion and pelvis rotation ($r_s = 0.32$, $p < 0.001$ and $r = 0.63$, $p < 0.001$, respectively), and the leading leg's peak hip flexion angle ($r = 0.44$, $p < 0.001$).

Proximal variables that had a statistically significant correlation (range: 0.37 - 0.63) with peak shoulder IR angular velocity, were included in a stepwise regression model to evaluate their contribution to the variance in peak shoulder IR angular velocity (Table 11). Proximal variables displaying non-significant effects on the model were removed.

Table 11 - Contribution of the proximal segments to the variance in peak shoulder IR angular velocity.

Kinematic variable	R^2	*F* value	*p* value
Hip extension[a]	0.18	1.13	0.29
Hip extension[a] + pelvis rotation	0.31	21.7	<.001
Hip extension[a] + pelvis rotation + pelvis rotation ROM excursion	0.44	25.6	<.001

a = trailing leg, pelvis rotation = °/s, hip extension = °/s, ROM = range of motion.

In terms of the association between pelvis kinematics and the shoulder ROM, the results showed a positive correlation between shoulder peak ER angle and peak pelvis rotation angular velocity ($r = 0.23$, $p = 0.01$) and pelvis rotation ROM excursion ($r = 0.36$, $p < 0.001$). Similarly, a positive correlation was observed between shoulder horizontal abduction angle at MER and peak pelvis rotation angular velocity ($r_s = 0.25$, $p = 0.006$) and pelvis rotation ROM excursion ($r_s = 0.23$, $p = 0.013$).

5 Discussion

The main results of paper I and II, investigating the association between pre-season kinetic chain strength and power, and shoulder problems among handball players highlight the importance of pre-season TRP in terms of a potential protective role among male handball players. Regarding shoulder problems among female players, the results point towards a more complex interaction between participation-related risk factors and non-participation related risk factors. The results of this thesis further indicate that, for handball, shoulder load measured as internal load (self-reported perception of physiological load) is a better measure than external load (number of shots in league matches) as indicated by the stronger association with shoulder problems.

The results from paper III display a novel approach assessing the contribution of proximal segments´ kinematics to the shoulder IR angular velocity during a jump throw. The results point towards the importance of hip, pelvis and trunk musculature to transfer forces through the kinetic chain and towards the throwing arm in the absence of floor contact. Contrary to the proposed hypothesis, the results indicate that increased pelvis rotation ROM excursion and angular velocity may lead to increased shoulder loading, through the mechanism of larger shoulder ER angle and horizontal abduction angle at MER, potentially increasing the risk of developing a shoulder problem. Further, the findings show that strength and power training for central/back players should be programmed in accordance with the different throwing kinematics and different on-field demands compared to back/wing players.

5.1 Paper I and II

Because of the high physical intensity in handball, it should not come as a surprise that shoulder problems are common among both female and male handball players (Andersson et al., 2017; Asker et al., 2018; Clarsen et al., 2014; Rafnsson et al., 2021). The weekly prevalence of shoulder problems among male players from paper I was similar to results for Norwegian male players (27 % vs 28%, respectively) but the weekly prevalence of substantial shoulder problems was lower (4% vs 12%, respectively) (Clarsen et al., 2014). In a study looking at the effects of a shoulder problem prevention program, the weekly prevalence of substantial shoulder problems was reported to be 5% for the intervention group (Andersson et al., 2017), similar to the 4% prevalence reported in paper I. The average severity score in paper I was, however, notably lower compared to the severity score for both the intervention and control group from Andersson et al. (2017) (7.6/100 vs 29/100 (intervention) and 35/100 (control), respectively). This comparison is interesting since the intervention group from Andersson et al. (2017), had participated in the shoulder problem prevention program throughout the season while players from paper I kept their usual training schedule. Participants in paper I had high absolute pre-season strength, particularly high ER strength and high ER/IR ratio, compared to previously reported shoulder strength reference values for adult handball players (Cools et al., 2016), and high IMTP peak force compared to that measured in cohorts of rugby players (Darrall-Jones et al., 2015; Dobbin et al., 2018). High pre-season ER strength, ER/IR ratio and high IMTP peak force might therefore have influenced the low prevalence of substantial shoulder problems, and the low average severity score reported in paper I. These speculations are in line with findings from a systematic review looking at the effectiveness of strength training on sports related overuse injuries (Lauersen et al., 2014). Pre-season TRP has not been previously measured using the dynamic seated TRP test in a cohort of male handball players, so no direct comparison is available.

The results from Mirabito et al. (2022), showing shoulder ER strength to drop immediately after a pitching session and not return to baseline until three days later, also point to the potentially protective effect of high ER strength in the throwing shoulder. From a clinical perspective, a handball player with high ER strength and endurance should be able to tolerate greater eccentric load during the deceleration phase of throwing without experiencing a significant drop in ER strength or ER/IR ratio compared to baseline values. Furthermore, with high ER strength and endurance, a handball player should theoretically be able to avoid too much drop in the IR ROM following a throwing session (which is caused by increase infraspinatus muscle tension due to the high eccentric deceleration load (Mirabito et al., 2022)) and therefore potentially reduce the risk of GIRD and its negative effect (Almeida et al., 2013; Wilk et al., 2011). Due to the drop in maximal voluntary contraction and rate of force development immediately following eccentric exercises (Vila-Cha et al., 2023), it may be of great importance for male handball players to maintain high ER strength and endurance. These speculations are supported by the negative correlation found between pre-season ER strength and the individual prevalence of shoulder problems in paper I.

The weekly prevalence for shoulder problems and substantial shoulder problems in female players (paper II) was lower than previously reported by Andersson et al. (2018) (20% vs 26%, and 4% vs 9%, respectively). The pre-season ER and IR shoulder strength was, however, similar to published reference values for female players (Cools et al., 2016) but the IMTP and the TRP measurements conducted in paper II have not been used before in a study on female handball players, so no direct comparison is available. The results from paper II, showing a positive association between pre-season ER and IR strength and the severity score, and between pre-season IMTP and ER strength and the individual prevalence of substantial shoulder problems, were surprising and in contrast with the negative correlation between pre-season ER strength and the individual prevalence of shoulder problems found for the male cohort in paper I. These results from paper II contradict the proposed hypothesis and cause one to look at the claimed protective effect of high pre-season strength and power from a broader perspective. The comparison between results from paper I and paper II, along with additional analysis of their combined results, further highlights the potential sex-dependent differences in shoulder problems among handball players.

The average PSL (internal load) was similar between the sexes and was positively associated with the OSTRC-O2 severity score in both studies. However, the influence of the PSL on the severity score was mediated differently by the pre-season measurements in paper I compared to paper II. Female players with pre-season ER strength, TRP and IMTP one SD above the group´s mean had a stronger positive association between reported severity score and the PSL compared to weaker players, while the same association between PSL and the severity score was evident for male players with pre-season TRP one SD below the group´s mean. Possible explanations for this different pattern between males and females include factors such as squad size and the availability of players with high physical capabilities, but increased physical fitness has previously been associated with increased playing time in football (Silva et al., 2022) and improved performance in basketball (Garcia-Gil et al., 2018). Also, the top female handball division in Iceland includes fewer teams compared to the top male division (8 vs 12, respectively). It can therefore be speculated that female handball teams in the Icelandic top division include fewer players with high physical capabilities, compared to the male teams. If players' high physical fitness is linked to greater chances of winning games, the coaching staff may be more inclined to rely more on those players. As a result, playing time might be distributed among fewer female players compared to the male players, as physically strong female players might play an important role in both defense and offense, thereby increasing the cumulative shoulder load. These speculations are supported by the stronger correlation displayed between most of the pre-season measurements and the external load for female players compared to the males and by a larger 95% CI of the average external load among the female players. Moreover, the mixed model ANOVA results showed how sex mediated the association between the pre-season strength and power (relative to body weight) and the OSTRC-O2 severity score differently. Due to sex-dependent differences in physical development, male teams may be more likely than female teams to include young players who are physically mature enough to withstand playing against older opponents. However, detailed information about handball exposure in terms of minutes per week was not documented in this thesis, so these explanations about the influence of increased playing time for more physically robust players on shoulder problems among female players remain speculative.

The way pre-season ER strength mediated the influence of external load on the severity score differently for male vs females was very interesting and challenging to explain. While the external load had no association with the severity of shoulder problems for the male players, female players with low pre-season ER strength were able to throw more shots while reporting lower severity score. One possibility is that female players with low pre-season ER strength might have had overall low pre-season strength and power and therefore decreased ball velocity while throwing, leading to less deceleration and eccentric load on the posterior rotator cuff. However, the interaction plot (Figure 8) showed no association between the severity score and external load for female players with ER strength one SD above the group´s mean, questioning the clinical meaning of this association between external load and the severity score for female players with low pre-season ER strength.

Another possible explanation for the sex-dependent results may relate to throwing technique and kinematics. Serrien et al. (2015) examined the throwing kinematics in a group of male and female handball players during a standing throw with a run up and the results showed female players to reach a larger peak ER angle during the cocking phase (Serrien et al., 2015). Larger peak ER angle has been associated with "improper trunk rotation sequence" and increased load being placed on the shoulder in baseball pitchers (Oyama et al., 2014). The increased soft tissue load that follows a larger ER peak angle might also be associated with increased instability symptoms, but results from Myklebust et al, showed instability symptoms to be common among Norwegian female handball players with current shoulder pain (Myklebust et al., 2013). In throwing, achieving peak trunk rotation angular velocity closer to the moment of ball release is believed to have a protective effect on the shoulder by reducing joint loading (Aguinaldo et al., 2007). The results from Serrien et al. (2015) showed that female handball players exhibit different timing of peak angular velocity compared with their male counterparts, as they reached peak trunk flexion and pelvic tilt angular velocities earlier in the throwing sequence. Interestingly, female players had in fact started to accelerate towards trunk extension when male players reach their peak trunk flexion. This earlier timing of peak angular velocity may interfere with the optimal proximal-to-distal transfer of energy through the kinetic chain and cause the shoulder to compensate. In contrast, van den Tillaar et al. (2012) found no significant gender-related kinematic differences in their analysis of the throwing motion, except for male players reaching higher ball velocity. A key difference between those two studies is that Serrien et al. (2015) looked at a standing throw with a run-up while van den Tillaar et al. (2012) analysed a standing throw without a run-up. Being able to utilize the run-up to increase the proximal segmental angular velocity likely explains to some extent the differences between those two studies, as peak pelvis and trunk angular velocity has been shown to be higher in a standing throw with a run-up compared with without a run-up (Wagner et al., 2011). Further, as shown by Serrien et al. (2015), most of the sex-dependent kinematic differences were found during the acceleration phase. One could therefore argue that as the acceleration phase is longer when throwing with a run-up, there is increased likelihood of capturing sex-related differences. However, no studies have compared sex-related kinematic differences in handball during a jump throw. Until such studies have been conducted, the influence of jump throw throwing kinematics and possible sex-related differences on the prevalence and severity of shoulder problems in handball players remain speculative.

Papers I and II are the first prospective studies to document shoulder load in handball, using the novel ways of PSL to capture internal load and number of shots per player during league matches for external load. Results from papers I and II indicate that PSL had more consistent association with severity of shoulder problems compared to external load as shown by the mixed model ANOVA results (both the published and additional thesis analysis). The optimal way to document shoulder load among overhead athletes has been debated (Schwank et al., 2022), but the results from paper I and II indicate that PSL, compared to external load, is better suited to capture shoulder load in handball as it enables the players to subjectively evaluate the cumulative defensive and offensive shoulder load, during training and competition. External load, in the form of total numbers of shots in league matches, gives some indication of the throwing load and should therefore also be included when health practitioners are working with handball players in a clinical setting. However, it does not capture the absolute external load as it misses things like long passes during matches and training, number of shots during training or number of defensive tackles during matches and training. The external load in handball can also fluctuate greatly, depending on factors like playing time, on-field positions and tactical decisions, further supporting the use of internal load measurements like PSL to capture the cumulative shoulder load in handball.

5.2 Paper III

Paper III is the first cross-sectional study to analyse the contribution of proximal segments´ kinematics to the shoulder kinematics in a jump throw and to compare the kinematics between different playing positions in handball. The results display the kinematic characteristics of the jump throw and the utilization of the proximal-to-distal sequence for transferring forces through the kinetic chain towards the throwing arm, in the absence of floor contact.

On average, the proximal-to-distal sequence was utilized for all participants during the jump throw, except for peak angular velocity of the leading leg hip flexion being reached after the peak pelvis rotation and peak elbow extension occurring before peak shoulder IR. Those results are in line with findings from Wagner et al. (2011) and in line with previous studies indicating that the segmental sequence during the throwing motion is not always strictly proximal to distal (Marshall & Elliott, 2000; Serrien & Baeyens, 2018). Central/back players reached peak angular velocity earlier within the defined throwing motion for all segments compared to wing/pivot players, with a statistically significant difference being found for the timing of the trailing leg hip extension, leading leg hip flexion, elbow extension and shoulder IR. Central/back players also displayed higher average peak angular velocity for all segments, except for thorax rotation. Central/back players are generally further away from the goal when shooting, so the need for reaching high ball velocity is higher compared to that required for wing/pivot players, potentially explaining the group differences for peak angular velocity. Other factors, like body height might also explain the central/back players' ability to reach higher angular velocity (Wagner et al., 2010). Wing/pivot players displayed larger SD regarding the timing of peak segmental angular velocity, particularly for the timing of peak hip extension, hip flexion and pelvis rotation angular velocity, which might be explained by their tendency to wait for the goalkeeper's reaction before initiating the throwing motion. Wing/pivot players displayed also larger SD for the peak angular velocity values for all segments analysed. Many of them have likely experienced playing as central/back players during their youth, before transitioning into a wing player when reaching elite level. Some wing players may therefore still have certain elements of central/back player throwing technique, possibly explaining the larger SD in peak angular velocity values.

Different on-field demands between central/back players and wing/pivot players may also explain the group differences found for the ROM excursion of the leading leg hip flexion, pelvis rotation, thorax flexion and shoulder rotation. The larger thorax flexion ROM excursion for central/back players indicates increased use of the abdominal muscles to enhance the acceleration phase of the jump throw. However, detailed analysis of the abdominal muscle activity during the jump throw is needed before further speculations can be made. Central/back players achieved also significantly greater peak angles for shoulder ER and horizontal abduction, potentially influencing higher shoulder IR angular velocity through a larger stretch-shortening cycle of the internal rotation muscles, like subscapularis, pectoralis major and latissimus dorsi. However, in terms of injury risk, increased shoulder ER and horizontal abduction angles during the cocking phase of throwing have been associated with increased shoulder stress (Manzi et al., 2021; Oyama et al., 2014; Takagi et al., 2015), making central/back players potentially more vulnerable for developing shoulder problems. Also of great interest, and contrary to the proposed hypothesis, a positive correlation was observed between the pelvis kinematics and shoulder ER angle and horizontal abduction angle at MER. That indicates that the on-field demands of reaching high ball velocity, through the mechanics of increased pelvis rotation ROM excursion and angular velocity, might come with the cost of increased shoulder soft tissue load. Considering the different on-field demands and kinematic characteristics of central/back players, these results indicate a potentially increased risk of developing overuse shoulder problems, compared to wing and pivot players. The physical training and load management of central/back players therefore needs to be executed with their unique on-field demands in mind.

As expected, both the peak trailing leg hip extension and leading leg hip flexion angular velocity were positively correlated with peak pelvis rotation angular velocity. That association supports a previously made postulation that a lack of floor contact for the cocking and the acceleration phases during the jump throw calls for different kinds of movement strategies to accelerate the pelvis and transfer forces to the throwing shoulder (Wagner et al., 2011). During a standing throw, the pelvis accelerates over the braced leading leg at floor contact. The lack of floor contact during the jump throw highlights the importance of the "mid-air" trailing leg hip extension to accelerate the pelvis, further supported by the strong positive correlation between these two variables. Interestingly, the peak leading leg hip flexion occurred after the peak pelvis rotation, so the role of the leading leg hip flexion likely serves to decelerate the pelvis rotation and further transfer forces up the kinetic chain. The positive correlation between the pelvis rotation and the leading leg hip flexion angular velocities indicates that as the pelvis rotates faster, the faster the hip must flex to decelerate and stabilize the pelvis. The role of the leading leg hip flexion kinematics for efficient energy transfer up the kinetic chain is also supported by the positive correlations between the shoulder IR angular velocity and both leading leg hip flexion ROM excursion, and the peak leading leg hip flexion angle. However, information about the hip joint muscle activity during the jump throw is lacking, indicating a gap in the current literature that warrants further investigation.

The lack of correlation between peak angular velocity for thorax rotation and shoulder IR was surprising and in contradiction to the proposed hypothesis, as were the non-statistically significant group differences regarding all thorax rotation kinematics variables. A possible explanation is the definition of the pelvis and thorax as separate segments in the kinematics analysis, with the thorax calculated with respect to the pelvis and the pelvis with respect to the global reference system, but not as a single segment as previously done (Wagner et al., 2010). Both hips and pelvis peaked earlier in terms of angular velocity within the throwing motion compared to thorax rotation. It is therefore likely that a large part of the forces had already been produced by the hips and the pelvis, limiting the need for a large thorax rotation force production. The definition of a two-segment trunk also likely explains why peak angular velocity values for thorax rotation were considerably lower than previously reported (Wagner et al., 2010). Different filtering strategies used during the data analysis may also explain why the peak elbow extension and shoulder IR angular velocity presented here were considerably lower compared to previously reported results (Wagner et al., 2010). The absolute angular velocities values for thorax rotation, shoulder IR and elbow extension should therefore be interpreted with caution.

Studies have repeatedly indicated the importance of pelvis kinematics for increased throwing performance (higher ball velocity) (van den Tillaar et al., 2013; Wagner et al., 2010; Wagner et al., 2011). Although, ball velocity was not documented in this study, multiple studies have associated higher shoulder IR angular with higher ball velocity (van den Tillaar & Ettema, 2007; Wagner et al., 2010; Wagner et al., 2011). The kinematic analyses presented in this thesis showed peak angular velocity of the trailing leg hip extension, pelvis rotation and thorax flexion, and leading leg hip flexion and pelvis rotation ROM excursion all to be positively correlated with peak shoulder IR angular velocity. The stepwise regression model further showed that the three most proximal segments of the hip joint and pelvis explained 44% of the variance in the peak shoulder IR angular velocity. This contribution of the proximal segments to the throwing shoulder kinematics highlights the need for adequate hip and abdominal muscle strength and power to enhance jump throw performance. Trunk flexion angular velocity has previously been linked to increased ball velocity (Wagner et al., 2010) although this variable did not have a significant influence on the stepwise regression model presented here. A possible explanation is the correlation between peak thorax flexion angular velocity and other more proximal kinematic variables in the model, introducing collinearity into the regression model.13

5.3 Limitations and methodological considerations

This thesis has several limitations. According to the priori power analysis, an insufficient number of participants was reached, limiting the generalizability of the association between the pre-season strength and power measurements and the OSTRC-O2 results. The OSTRC-O2 asked about self-reported shoulder problems and PSL for the past seven days so the chance of recall bias must be acknowledged. A recommended gatekeeping logic was used when analysing the OSTRC-O2 results to increase consistency (Clarsen et al., 2020). If a participant received zero points in the first OSTRC-O2 question, then a total severity score of zero was applied, all further questions considered redundant, and the questionnaire marked completed. Also, if a participant scored 25 points on the fourth question, a total severity score of 100 was applied and all previous questions considered redundant. Applying that gatekeeping logic has been shown to lower the self-reported prevalence of shoulder problems but still capture 98.5% of all substantial problems (Clarsen et al., 2020). The reported prevalence of shoulder problems and severity scores in Papers I and II may therefore have been lowered due to the gatekeeping method applied.

For paper II, the total number of shots per player in league matches as a definition of external load gives some indication of the throwing load but is limited, as it does not account for long passes during matches and training, the number of shots during training or number of defensive tackles during matches and training. However, accurately documenting the number of tackles, passes and shots per player during training is impractical in a semi-professional environment like the Icelandic top division.

It was not possible to control for the participants´ training load prior to any of the pre-season data collections, as each team and each participant had their own training schedule. It is therefore possible that fatigue might have to some extent influenced the results of the pre-season measurements and the jump throw motion analysis. The main limitation for paper III was the laboratory set up. The handball goal was positioned closer than in the usual training or match-like environment potentially influencing the absolute kinematics values, but no participants felt that the set up interfered with his ability to execute the jump throw. As the ball velocity was not analysed in paper III, the potential influence of proximal kinematics on jump throw performance (ball velocity) remains somewhat speculative. Further, participants were instructed to execute the jump throw in a normal fashion which likely resulted in lower absolute kinematic values compared to if participants had been instructed to throw as fast as possible.

6 Conclusions

The results of this thesis highlight multiple possible risk factors for shoulder problems among handball players, as well as their interaction and how sex-specific factors can significantly influence the development of overuse shoulder problems. Results from paper I indicate that low pre-season TRP among elite male handball players might make the throwing shoulder more vulnerable regarding tolerance for an increase in load. This points towards the importance of pre-season conditioning to increase TRP among male handball players and thereby provide the foundation for optimal energy transfer from the proximal kinetic chain to the throwing shoulder. Importantly, results from paper II highlight the complex interaction between participation related risk factors and non-participation related risk factors for female handball players. Teams may need to recruit greater numbers of players with high physical capabilities to be able to lower the shoulder load among their players during competition. That might influence the association between high pre-season strength and power and shoulder problems among female players. There is a great need for more sports science research to be exclusively conducted on female athletes, as underscored by the popular phrase "women are not small men".

Results from paper III highlight the importance of efficient force transmission through the kinetic chain and towards the throwing shoulder and indicate that different on-field demands of different playing positions influence players' throwing kinematics. To prepare an athlete for the upcoming training and competition load in the most efficient way, it is imperative to consider in detail the type of load the athlete needs to withstand. Pre-season strength and power training should therefore not be "one size fits all" as is often the case in a semiprofessional environment, but rather an individualized strength and power program, emphasizing hip, pelvis and abdominal strength and power.

Future studies should continue to assess the jump throw and examine electromyographic data on hip, pelvis and abdominal muscle activity during the jump throw. Information about the lower limb/core muscle activity during the jump throw might lead to new isometric or dynamic strength tests of more specific relevance than the IMTP for pre-season screening for handball players. Future research should also continue to examine possible differences in sex-specific throwing kinematics and, if any, assess their influence on performance, as well as the prevalence and severity of shoulder problems among male and female handball players. Whether a truly optimal way of throwing exists, or whether an optimal load management is more important than the perfect technique, is a challenging question for future researchers. Similarly, the extent to which suboptimal pre-season strength and power, or suboptimal throwing technique matters, as long as the athlete avoids doing too much, too quickly, requires further investigation. Continued research could also examine sex-specific throwing kinematics for different age groups and assess whether physical development during puberty influences the jump throw kinematics. Results from such studies could potentially highlight a certain specific stage in a player's development that is best suited for coaching an optimal throwing technique.

As always, prevention is better than cure, so health professional working with handball players should continue to focus on implementing preventative measures before shoulder problems come knocking on the door.

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Original Publications

Paper I

Paper I

Paper II

Paper II

Paper III

Paper III

Appendix A

The Oslo Sports Trauma Research Center Overuse Injury Questionnaire – Icelandic translation

Tengsl styrks og kraftmyndunar í neðri útlimum og bol og álagsmeiðsla í öxl hjá leikmönnum í handknattleik

Við óskum eftir að þú svarir öllum spurningunum óháð því hvort þú hafir einkenni eða verki í öxl.

ATH - einungis er verið að spyrja um einkenni frá **kastöxl**! Svaraðu með því að velja það svar sem þér finnst passa best. Ef þú ert ekki viss um hverju þú átt að svara, reyndu samt að svara eins vel og þú getur.

Með einkennum frá öxl er átt við verki, eymsli, stífleika, óstöðugleika, los eða önnur óþægindi. Takk fyrir!

1) **Þátttaka -** Hefur þú átt í einhverjum erfiðleikum með að taka þátt í æfingum og keppni vegna einkenna frá öxl síðustu 7 daga?
   a. Full þátttaka án einkenna frá öxl
   b. Full þátttaka en með einkenni frá öxl
   c. Skert þátttaka vegna einkenna frá öxl
   d. Gat ekki tekið þátt vegna einkenna frá öxl

2) **Aðlögun á æfingum/keppni** - Hve mikið hefur þú þurft að aðlaga þátttöku í æfingum og keppni vegna einkenna frá öxl síðustu 7 daga?
   a. Ekkert aðlagað keppni/æfingar
   b. Lítið aðlagað keppni/æfingar
   c. Töluvert aðlagað æfingar/keppni
   d. Mikið aðlagað æfingar/keppni

3) **Frammistaða** - Hve mikið hafa einkenni frá öxl haft áhrif á frammistöðu þína á æfingum og keppni á síðustu 7 dögum?

   a. Engin áhrif
   b. Lítil áhrif
   c. Töluverð áhrif
   d. Mikil áhrif

4) **Verkur** - Hve mikið hefur þú upplifað axlarverki í tengslum við handbolta á síðustu 7 dögum?

   a. Enginn verkur
   b. Lítill verkur
   c. Töluverður verkur
   d. Mikill verkur

5) **Álag** - Hversu mikið álag hefur verið á öxlinni síðastliðna viku?

0 = Alls ekkert álag
0.5 = Mjög, mjög lítið (varla merkjanlegt)
1 = Mjög lítið
2 = Lítið
3 = Miðlungs
4 = Nokkuð mikið
5 = Mikið
6 =
7 = Mjög mikið
8 =
9. = Mjög, mjög mikið (næstum hámarks álag)
10 = Hámarks álag