"Investigating intrinsic properties and external load measures as potential risk factors for shoulder injuries in elite water polo players"

Félix Croteau

School of Physical and Occupational Therapy

McGill University

Montreal

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List of abbreviations

CI = confidence interval

CV = coefficient of variation

ER = external rotation

ER:IR = external over internal rotation ratio

ES = effect size

FINA = Fédération Internationale de Natation

HR = hazard ratio

ICC = intra-class correlation

IMU = inertial measurement unit

IR = internal rotation

ISP = infra-spinatus

GPS = global positioning system

LHB = long head of biceps

LPM = local positioning measurement

MDC = minimally detectable change

MRI = magnetic resonance imaging

NOS = Newcastle-Ottawa Scale

OR = odds ratio

RC = rotator cuff

ROM = range of motion

SD = standard deviation

SEM = standard error of measurement

SLAP tear = superior longitudinal antero-posterior tear

SSC = sub-scapularis

SST = supra-spinatus

TROM = total range of motion

UR = scapular upward rotation

Abstract

Shoulder injuries are the most common of all overuse injuries in the sport of water polo. By their nature, they can be prevented with adequately targeted strategies.

First, a systematic review was conducted to collate information on injury epidemiology in water polo players as well as their underlying risk factors. Data was collected from three databases (Pubmed, Embase and SportDiscus), and articles were screened and rated for quality by separate reviewers. The results showed that traumatic injuries to the hands and face were most common during competitions, and that shoulder injuries were highly prevalent throughout training periods across different age groups. Longitudinal studies in water polo examining injury risk factors were limited, albeit one group showing an association between shoulder rotators weakness, lack of flexibility, and incidence of new injuries in sub-elite water polo players.

Second, a validation study was performed in order to evaluate the extent to which shoulder strength measurements with hand-held correlated with those of an isokinetic dynamometer. Repeated measures of internal rotation and external rotation strength were obtained from 39 water polo players with both devices. There was moderate to good validity with the isokinetic device and good to excellent reliability of repeated isometric measurements. Bland-Altman plots revealed that hand-held measurements consistently underestimated strength values in the stronger individuals in the study.

Third, a prospective study was designed to measure baseline history of shoulder injury, shoulder strength, range of motion, and scapular upward rotation of male and female national team water polo players. New shoulder injuries were monitored over nine months. Injuries were identified as complaints requiring medical attention. Shoulder strength was

measured using an isokinetic dynamometer. Shoulder range of motion was measured using a standard goniometer. Scapular position was measured using a digital inclinometer. Independent t-tests evaluated group differences in risk factors between healthy players and those that experienced a shoulder injury over the nine-month follow-up. A logistic regression model was fit to evaluate the relationship of these factors to new shoulder injuries. Results showed that lack of internal rotation flexibility and changes in scapular upward rotation were associated with injury incidence. Injury risk was increased significantly based on the presence of a history of recent shoulder injury and increased scapular upward rotation.

Finally, an experiment was designed to automatically count the number of overhead throws performed during training using machine learning classifiers and inertial measurement unit (IMU) data. Two cameras positioned at opposite ends of the pool were used to label the actions concurrently to the IMU measurements, and inform two machine learning classifiers (support vector machine and artificial neural network) to generate a pattern recognition algorithm. An analysis of the proportions of predicted vs observed events was undertaken to estimate the performance of the classifiers. Both classifiers showed high performance at predicting overhead throws, with neural networks proving to be much shorter to execute.

Abrégé

Les blessures aux épaules sont les blessures par surutilisation les plus communes au water-polo. De par leur nature, elles peuvent être évitées avec des stratégies adéquates.

Premièrement, nous avons produit une revue systématique de la littérature sur l'épidémiologie des blessures au water-polo ainsi que sur leurs facteurs de risque. Les articles ont été identifiés dans trois bases de données (Pubmed, Embase et SportDiscus), puis lus et leur qualité évaluée par des réviseurs séparés. Les résultats indiquent que les blessures au niveau du visage et des mains se produisent souvent lors des compétitions, mais que les blessures au niveau des épaules sont plus communes pendant les entraînements, et ce dans tous les groupes d'âge étudiés. Les études longitudinales sur les facteurs de risque sont limitées. Néanmoins, un groupe de chercheurs a démontré une association entre une faiblesse à la coiffe des rotateurs et un manque de flexibilité vis-à-vis d'une incidence de blessures à l'épaule chez des joueurs sous-élite.

En deuxième temps, nous avons performé une étude de validation pour évaluer la corrélation entre les mesures de force à l'épaule obtenues par un dynamomètre manuel comparé à un dynamomètre isocinétique. Des mesures répétées de rotation interne et de rotation externe furent obtenues de 39 joueurs de water-polo avec chacun des appareils. Les résultats indiquent une validité modérée à bonne vis-à-vis de l'appareil isocinétique et une fiabilité bonne à excellente pour les mesures répétées. Des diagrammes de Bland-Altman révèlent que l'appareil manuel sous-estime les individus plus forts dans cette étude.

Troisièmement, une étude longitudinale fut mise en place pour mesurer l'historique de blessure à l'épaule, la force de la coiffe des rotateurs, l'amplitude articulaire, et la rotation supérieure scapulaire chez des joueurs de water-polo des équipes nationales

masculine et féminine. L'incidence de nouvelles blessures à l'épaule fut enregistrée durant les neuf mois suivants. Les blessures furent définies comme toute plainte nécessitant une attention médicale. La force fut mesurée avec un dynamomètre isocinétique. L'amplitude articulaire fut mesurée avec un goniomètre traditionnel. L'alignement scapulaire fut mesuré avec un inclinomètre digital. Des tests *t* ont servi à évaluer la différence entre la moyenne pour ces facteurs de risque chez les joueurs blessés vis-à-vis des joueurs sains à la fin de la période de suivi de neuf mois. Un modèle de régression logistique fut bâti pour évaluer l'importance de ces facteurs. Les résultats indiquent qu'un manque d'amplitude articulaire en rotation interne et un manque de rotation supérieure scapulaire sont reliés à l'incidence de nouvelles blessures. De plus, le risque de nouvelle blessure était significativement plus grand avec un historique de blessure précédente accompagné d'une augmentation de rotation supérieure scapulaire.

Pour terminer, une étude fut élaborée pour conter automatiquement le nombre de lancers exécutés à l'entraînement avec des centrales inertielles et des outils d'apprentissage machine. Deux caméras positionnées aux extrémités de la piscine ont servi à identifier les incidences de lancers, pour ensuite informer les deux outils d'apprentissage machine (*support vector machine* et réseau de neurones). L'analyse des événements observés vs les événements prédits fut entamée pour évaluer la performance des classificateurs. Les deux outils ont démontré une grande performance de prédiction, mais les réseaux de neurones sont beaucoup plus rapides d'exécution informatique.

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Statement of originality

This dissertation includes four manuscripts that are included as Chapters three through six. The manuscripts from Chapters three, four and five have been published in peer-reviewed journals. The manuscript from Chapter six is currently under review by a peer-reviewed journal.

The manuscript from Chapter 3 titled *"Prevalence and Mechanisms of Injuries in Water Polo: A Systematic Review"* was the first systematic review of all injuries in water polo. Two previous authors had exclusively focused on shoulder injuries in this population. Our review showed that concussions are likely under-reported in this sport, and that injuries to the lower body should receive further attention as well.

In Chapter 4, the manuscript *"Hand-held shoulder strength measures correlate with isokinetic dynamometry in elite water polo players"* was the first work to estimate the reliability of hand-held dynamometers in water polo players and compare the measurements with the gold standard isokinetic dynamometers. The findings show that although the two methods correlate well, isometric devices are inferior to measure peak maximal values and that the ratios of agonists to antagonists calculated from these measures do not correlate with those obtained from an isokinetic device.

In Chapter 5, titled *"Risk Factors for Shoulder Injuries in Water Polo: a Cohort Study"*, our work sets itself apart via the inclusion of previous injuries as a confounder, as well as scapular upward rotation. In a logistic regression analysis, these two variables were the most significant in explaining the likelihood of participants sustaining new injuries.

Finally, Chapter 6: *"Automatic Detection of Passing and Shooting in Water Polo Using Machine Learning"* was the first study to attempt to capture external workload in the water polo population using an automated method. Our work has brought a technology used in other team sports to this field and detailed a successful method for workload collection via machine learning classifiers.

Contribution of authors

Mr. Félix Croteau was the first author for all four of the manuscripts listed in this dissertation because he was responsible for proposing the research questions, developing the research design, obtaining funding and equipment, performing data collection and analysis, interpreting the results and writing of all four manuscripts.

For Chapter 3, Harry Brown is listed as the second author in recognition for his contribution to the data extraction process, the study quality assessment and his assistance with the final written version of the manuscript. Dr David Pearsall and Dr Shawn Robbins both contributed to the research design and provided insight for the final version of the manuscript. Dr Robbins further participated in screening of the articles included in the systematic review, and shared key insights for the methodological rigor of the process and data analysis.

For Chapter 4, Dr David Pearsall and Dr Shawn Robbins both contributed to the research design and provided insight for the data analysis and the final version of the manuscript.

For Chapter 5, David Paradelo was listed as the second author in recognition for his role in the development of the research questions and design, as well as his input concerning the final written manuscript. Dr David Pearsall and Dr Shawn Robbins both contributed to the research design and provided insight for the final version of the manuscript. Dr Robbins provided ongoing assistance with data analysis and interpretation of the results.

For Chapter 6, Francois Thenault is listed as the second author in recognition for his major contribution to the data processing and analysis portions of this study. Dr Stefanie

Blain-Moraes participated in the finalization of the data processing and analysis, as well as the revision of the final manuscript. Dr David Pearsall and David Paradelo both provided insight for the interpretation of the results and to review the manuscript. Dr Robbins provided ongoing assistance with data analysis, interpretation of the results as well as the editing of the final manuscript.

Chapter 1. Introduction

1.1 Rationale

Water polo is a popular aquatic team sport, played across the world and featured in the men's Olympic Games since their modern era in 1900 (women's water polo joined in 2000).[1] The sport is played by six players per team with an additional goalkeeper in a pool at least two meters deep. Players must swim across the pool (25m for women and 30m for men), and grapple versus their opponents to gain position to shoot the ball into their net. This requires bouts of very high-intensity activity, spaced with lower intensity periods.[2] A match continues this way for four periods of eight minutes, with two breaks of two minutes and a mid-game pause of five minutes, for a total of approximately 55-60 minutes per match.

Given the high level of contact that occurs during games, injuries are common in this sport, ranked with the highest injury prevalence of all aquatic sports (16.0-22.7% for males vs 8.7-14.4% for females at the Olympic Games).[3,4] Most of these contact injuries affect the head and the hands of the players, and include concussions, lacerations and fractures.[5] However, observational findings show that overuse injuries are more common than acute ones in this sport due to the large volumes of swimming and overhead shooting.[6] More specifically, the shoulder area is consistently targeted as the area for the most complaints of pain in water polo players.[7,8]

The circumstances leading to sports injuries are multifaceted, and effective prevention strategies must address different risk factors to be successful.[9] Current sports injury models explain the emergence of these events as the result of complex interactions between a web of determinants, resulting in profiles of participants that are at higher risk for injury (see Figure 1.1). The determinants in this model can have a different weight in the resulting profile, and can further interact with other determinants in a non-linear manner.[10] Some of these variables may be intrinsic to the participants, such as their sex, age, fitness and psychological state.[11] Furthermore, extrinsic variables may be related to the environment where the athletes are participating, including specific equipment, weather, playing surfaces, or other social factors.[12] The presence of these factors has a non-linear relationship with injury incidence, with progressive exposure being potentially beneficial, as it promotes the necessary adaptations to tolerate the sporting context successfully.[13] Alternatively, the interaction of some determinants may expose the athletes to new injuries (for example very large and sudden increase in training volume coupled with concomitant weakness). As it was shown to be a confounder to many of these interactions, training load is an important variable to consider when looking at this sports injury framework. Gradual exposure to training can have a protective effect in athletes, whereas excessive volumes can increase the accumulation of "fatigue" and predispose athletes to injury under a similar situation.[9,10,14]

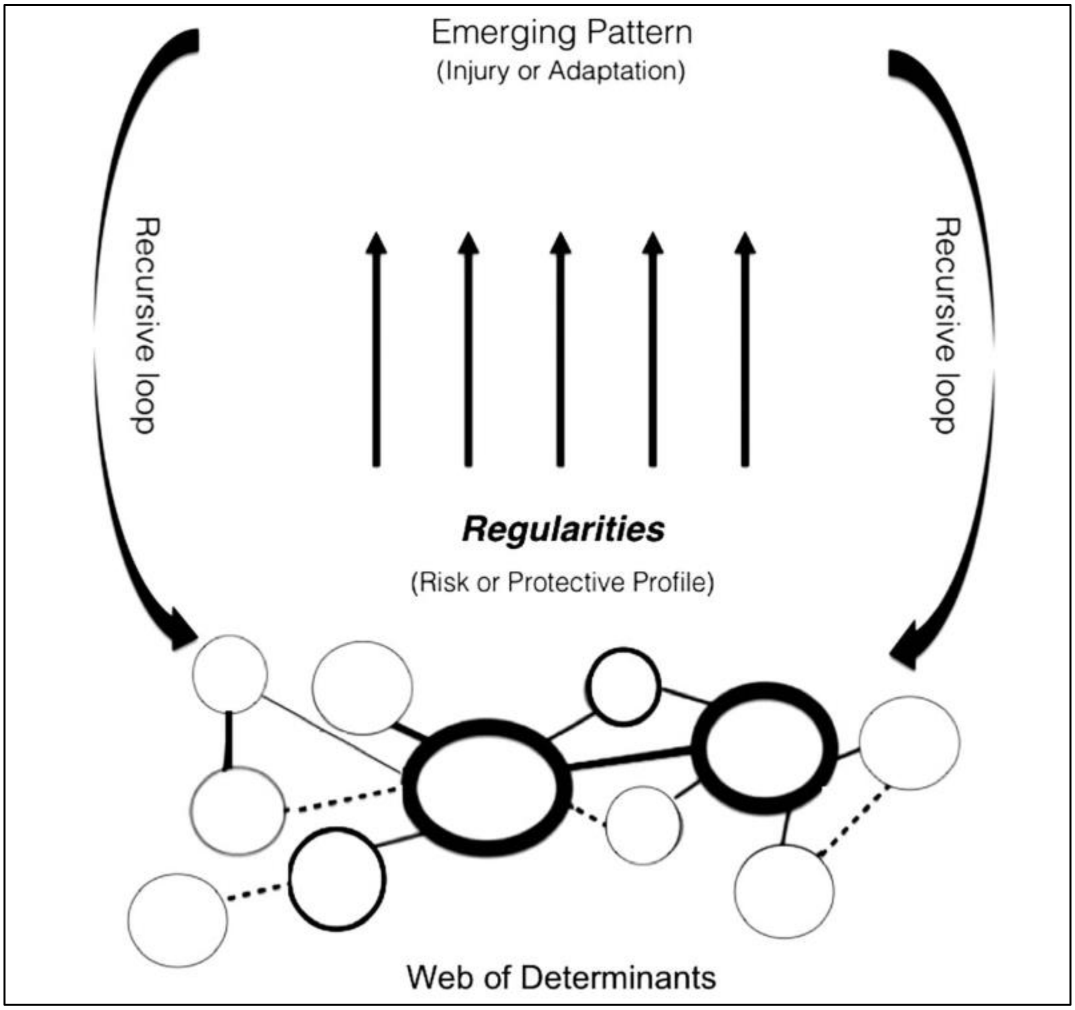

Figure 1.1 Complex systems model shows how different determinants have a weight in the emergence of a risk profile (large circles representing more weight). The determinants interact with each other, with the thicker outline showing those that have more connections. Dotted lines represent weak interactions, whereas the thicker lines suggest stronger associations.

1.2 Problem statement

According to van Mechelen's fundamental principles of sports injury prevention, successful strategies follow a course of four phases.[15] First, we must quantify the burden of injury in a sport with adequate rigor to establish prevalence of incidence of injuries. Second, the mechanisms leading to these injuries must be sought and understood. Third, prevention strategies should be put in place to address mechanical deficiencies. Finally, an ongoing process of injury surveillance must track the efficacy of these interventions at truly diminishing injury incidence, and further inform improved strategies to keep athletes safe.

Injury prevalence and injury risk factors in water polo were incompletely described in the literature, and thus this was the first step to address. Only two systematic reviews had been published on the topic, and both focused exclusively on the shoulder area.[6,16] A thorough review was necessary to understand the burden of injuries in this sport, as well as the hypothesized risk factors leading to their occurrence. Pre-existing injuries can precipitate injuries to other body areas in the same athletes,[12] and hence a lack of appreciation for the full spectrum of pathologies in water polo would limit our understanding of the factors related to shoulder injuries.

Next, we undertook to examine the mechanisms of the injuries identified. No prospective studies had investigated these risk factors to evaluate their relative effect on shoulder injuries at the outset of this thesis. The common proposed risk factors for shoulder injuries in water polo include large training volumes, as well as scapular dyskinesia, insufficient strength and deficiencies in flexibility of the rotator cuff. These risk factors have only very briefly been explored in the past, primarily with elite male athletes.[17,18] Therefore, prospective investigation of other risk factors such as previous injury, scapular dyskinesia and workload remained absent. However, a method to quantify training load was lacking, thus limiting the ability to create interventions based on management of workload. The exploration of wearable technology provides an ideal option to capture the wide variety of movements typical of water polo.[2]

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Chapter 2. Background

2.1 Risk factors for shoulder injuries in water polo

A recent systematic review of shoulder injuries in water polo identified the following mechanisms as the main risk factors for their development: “volume of shooting, [lack of] range of motion, scapular dyskinesis, strength imbalances, proprioceptive deficits and altered throwing kinematics”.[1] The relationships between injuries and range of motion or strength deficits were investigated in two cohorts. However, the other risk factors mentioned above were only observed in single time-point study designs, and their causative relationship with injuries remains elusive. Below is a synthesis of the available investigations for each of these risk factors. Data from studies with healthy vs injured players is favored, but comparisons with non-players or between dominant and non-dominant sides is presented when injury data is unavailable. Chapter 3 will present a more thorough review of injury studies examining water polo players.

2.1.1 Shoulder range of motion

The action of overhead throwing in water polo stimulates adaptations in mobility, more specifically an increased range of motion into external rotation of the dominant shoulder.[2] The consequence is a concomitant increase in the total arc of shoulder rotation on the dominant side in this population.[3] However, the association between lack of shoulder range of motion and injuries has not been reported consistently. In her 1993 cross-sectional study, Elliott found no association between shoulder pain and flexibility measurements in a group of 13 male elite water polo players.[4] However, Hams et al (2019) recently followed a group of 76 sub-elite (28 male and 48 female) players for 12 months after baseline testing, and found that the group with new injuries (n=14) showed significantly less total range of motion on their dominant shoulders compared to their non-dominant sides ($p<0.05$).[5] Further research is needed to verify the direction of this relationship.

2.1.2 Scapular dyskinesis

The simultaneous function of the scapula with the gleno-humeral joint is crucial when performing overhead throwing activities.[6] The capacity for the scapula to move in three degrees of freedom, along a thorax that can also move makes it difficult to quantify.[7] Two measurement methods have been documented in studies of water polo players: a static measure of scapular positions in different humeral elevation angles, and a dynamic measure of active range of motion using electromagnetic tracking systems. Witwer and Sauers (2006) found no significant differences between the dominant and non-dominant scapular upward rotation angle measured in a static position for 31 collegiate-level male water polo players ($p=0.68$).[2] However, in a study comparing 14 healthy players with 16 water polo players with shoulder impingement, Mukhtyar et al (2014) found a significant reduction in static scapular abduction in the injured players ($p<0.01$).[8] In the later study, measurements were taken both before and after an “intense practice” consisting mainly of swimming. Only the measurements obtained after the practice were significantly different between the healthy and injured players. Turgut et al (2018) performed an analysis of movements of the scapula in all three planes using electromagnetic tracking.[3] They found no significant differences between their 14 water polo players and 14 non-athletes in any direction ($p=0.29$-0.87); they also did not find any significant difference in scapular motion between the dominant and non-dominant shoulders of the water polo players ($p=0.13$-0.63). There have been no other electromagnetic tracking investigations of scapular dyskinesis in water polo comparing healthy and non-healthy players.

2.1.3 Strength imbalances

The most documented variable to investigate as a risk factor in this population has been strength, in both absolute and relative values, as well as a ratio of agonist and antagonist rotator muscles of the shoulder. The gold standard for this type of measurement is the isokinetic dynamometer, which can be used to obtain length-tension curves, as well as a multitude of strength parameters.[9] Studies of healthy water polo players (n=15-18) have consistently shown that they were significantly stronger than healthy controls (n=10).[10,11] However, the values obtained with this method vary based on the speed and mode of the test (i.e. concentric vs eccentric), as well as the position in which the participants perform the movement.[11] Therefore, it is not recommended to pool these values together and care must be applied when comparing findings across different studies. The alternative approach to measure strength consists of using a hand-held dynamometer. Hams et al (2019) performed two cohort studies of strength and injury incidence in sub-elite Australian water polo players using this second method. In their first study of 15 players (6 females and 9 males), they found significantly lower preseason internal rotation (IR) strength in an abducted shoulder position (p=0.04) and lower preseason external rotation (ER) strength in a neutral shoulder position (p=0.04) in the injured group compared to the healthy group.[12] In their next study of 76 players (48 females and 28 males), they found the same relationship between injuries (n=14) and lower IR (p=0.01) and lower ER (p=0.03) strength after 12 months.[5] However, in both studies, the ratios of external over internal rotation strength was not significantly different between the healthy and injured groups. This provides preliminary results that shoulder weakness is indeed related to shoulder injuries in sub-elite water polo players of both sexes, but this must be confirmed with other competition levels as well. Further analysis is required to establish whether ratios of ER over IR need to be measured in concentric, eccentric or combined approaches.[13,14] Thus far, a lower ratio of ER over IR has not shown consistent correlations with injuries in water polo players.

2.1.4 Proprioception deficits

One element of the sense of proprioception is "the conscious or unconscious awareness of joint position".[15,16] This can be measured clinically by asking the participants to reproduce a specific joint position and measuring the difference between the targeted vs demonstrated angle.[16] Mota and Ribeiro (2012) evaluated this ability in twenty healthy male water polo players by asking to reproduce a position of 30° of ER or 30° of IR after they had been previously positioned at that angle passively by the evaluators.[13] The median absolute error for IR position was 4.7° and 4.0° for ER. These values are reported as slightly higher than those observed in non-athletes, and the authors suggest that this may in turn inhibit optimal muscle control in overhead throwing motions and lead to overuse injuries.

2.1.5 Altered throwing technique

The throwing motion in water polo is unique compared with other overhead sports in respect to the fact that the players must create upward momentum without a firm base of support.[17] Studies of the penalty throw show that male players on average throw at 16.5-25.3m/sec,[18-20] whereas female players throw at 13.1-16.8m/sec.[18-23] These differences likely reflect throw type and sex differences in strength,[24] not only of the throwing arm but also of the lower body and one's ability to get a high vertical position in the water.[25-27] In a study of 17 injured vs 36 healthy male water polo players, Melchiorri et al (2011) found no significant differences in kinematic variables of elbow or shoulder angles or speeds.

However, the injured group demonstrated significantly longer trunk rotation time to perform a throw ($p<0.01$).[19] The fatigue from swimming to gain a good shooting position, as well as the contact with opponents to maintain it, can further increase the risk of injury during the throwing motion and decreases throw performance ($p<0.05$).[28,29]

2.1.6 Large shooting volume

As mentioned in Chapter 1.1, training volume is considered in the workload-injury model as a meaningful modifier to intrinsic risk factors. This reflects the fundamental fact that increased exposure to a hazardous sport increases the likelihood of eventually sustaining an injury. Therefore, it would be consistent with this proponent to consider summative exposure to water polo as an important risk factor for injuries. In a typical practice, players are required to swim large distances >1000m and throw the ball overhead for hundreds of repetitions.[18] Wheeler et al (2013) explored the relationship between overhead shooting and shoulder soreness in a small study of seven national level female water polo players.[30] The volume of overhead throws was recorded using video capture and manually coded for analysis during two weeks of training camps. The participants were also asked to rate their perceived shoulder soreness daily during this period on a numerical rating scale (1-10). Linear regression analysis showed that 74% of shoulder soreness was explained by shooting volume alone ($p=0.01$), and that shorter resting times between shots were contributing factors to increased soreness as well ($p=0.03$). Although studies are available to describe the physiological requirements of water polo players,[31-33] there has been no investigation relating workload and injuries in this population.

2.2 Measurement of risk factors for shoulder injuries

If we are to measure injury risk factors, we need to consider the validity of these measures and whether they can be easily implemented in a clinical setting. The intrinsic risk factors that individuals hold can be further separated into two groups: the modifiable and the non-modifiable. The later include fixed traits such as sex, age, years of participation in the sport, and history of a previous injury. The modifiable risk factors rather include characteristics such as strength, range of motion, technical skill, and fitness. These receive the most attention because they can be the targets of injury prevention strategies. Proper measurement of these characteristics is important not only to establish if the values indicate a higher risk athlete, but also to monitor improvement over time.

A recent review of risk factors for shoulder injuries in overhead sports (baseball (n=11), handball (n=6), swimming (n=3), volleyball (n=2), tennis (n=1) and basketball (n=1)) identified the following modifiable traits as consistently associated with higher rates of injuries: lack of range of motion, muscle weakness, scapular dyskinesis and high training load.[6] Here is a summary of the current methods used to measure the identified modifiable traits. Measurements of training load will be discussed in section 2.3.

2.2.1 Measurement of shoulder range of motion

Shoulder range of motion has been reported as a significant factor for shoulder injuries in multiple overhead throwing sports including baseball, handball, swimming, and water polo.[34] More specifically, mobility is measured in these sports for IR and ER. These values are then used to calculate total range of motion (internal + external), as well as external rotation gain (dominant external – contralateral external) and gleno-humeral internal rotation deficit (contralateral internal – dominant internal).[15] The two most common methods used to obtain measurements of range of motion include the standard goniometer and the digital inclinometer.[35,36] The standard goniometer has demonstrated high intra-rater reliability (intra-class correlations (ICC) = 0.85 to 0.96) in healthy participants[37,38] and in participants with unilateral shoulder pathology (ICC=0.94 to 0.99).[37-39] However, there is somewhat lower inter-rater reliability (ICC=0.82 to 0.95) suggesting that for longitudinal observations, the same examiner should perform the measurements consistently.[39]

2.2.2 Measurements of shoulder strength

Weakness of the rotator cuff muscles has been consistently considered as a risk factor for shoulder injuries in overhead sports.[6] The measurements of IR and ER strength can be used to calculate relative strength (strength / body weight), as well as ratios of ER over IR.[12] There are two main methods to estimate shoulder strength clinically: either using an isokinetic dynamometer, or with a hand-held device. The isokinetic dynamometer is the gold standard for this measurement, as it can be used to obtain length-tension curves, as well as test the participant in different contraction modes or speeds.[40] The intra-rater reliability for shoulder ER and IR mean torque is high, with ICC values of 0.82 to 0.98 observed on different machines with the test performed at 60°/sec.[41-45] Sources of increased variability in the data obtained with these tests comes from (1) installing the subject in a different position, (2) performing the tests at higher speeds, (3) doing eccentric contractions, or (4) attempting to calculate different ratios of agonists over antagonists. Significant differences ($p<0.05$) have been found when testing participants in supine versus seated, or with the arm in a sagittal, scapular or abducted plane of movement (coefficient of variation=7.1 to 19.1%).[46,47] Altogether, these findings suggest that a consistent setup must be selected for repeated measures of ER and IR torque on isokinetic devices, and that supine positions may yield more reliable findings.

The limitations of isokinetic dynamometers are that they are cumbersome, expensive, and require trained evaluators to operate. Alternatively, clinicians can measure isometric or eccentric strength of the shoulder rotators using hand-held dynamometers.[48] A recent systematic review for shoulder measurements was performed and the grouped data shows large ranges of intra-rater reliability (ICC=0.57 to 1.00) and inter-rater reliability (ICC=0.64 to 0.99).[49] Overall, the reliability of this tool is inferior to isokinetic devices, as has been concluded for various other movements of the shoulder as well.[50] There are three main factors that can directly influence the results of this test: (1) the position of the subject, (2) whether using “make” or “break” resistance, (3) and the strength of the evaluator. The make test implies that the evaluator matches the force of the participants, whereas they aim to break their contraction in the break test. The effect of position of the subject was discussed above for isokinetic devices, and relates to muscle length-tension curve dispositions. A study involving 201 healthy participants from various sports found no significant differences in intra-rater ICC between the make (isometric force) or break tests (ICC=0.83 to 0.93 vs ICC=0.83 to 0.91, respectively).[51] Finally, the capacity for an evaluator to reliably test a subject that is much stronger than themselves can bias the results that they measure.[12] Fixing the device to an external anchor does not consistently improve the reliability of this tool.[52,53]

There are very few studies investigating the concurrent validity and level of agreement of measures of shoulder strength between hand-held dynamometers and isokinetic dynamometers. Systematic reviews have focused on assessments of the lower extremity, showing different results based on the movement under evaluation (ICC=0.62 to 0.94).[54] Specifically regarding shoulder strength evaluations, results also showed a large range of agreement between the two methods in healthy populations (r=0.28 to 0.86).[55,56] No previous study has assessed the agreement between these methods of strength measurements in water polo players. This needs to be investigated to indicate whether previous findings can be pooled together, and to complement the work by Hams et al (2019) who focused on reliability alone without verifying validity of this method vs a gold standard.

2.2.3 Measurement of scapular dyskinesis

The scapulo-thoracic joint remains difficult to measure reliably in a clinical setting.[7,57] Dyskinesis refers to a pathological variation from what is considered “normal” scapula-thoracic motion.[58] In overhead athletes, a typical adaptive pattern tends towards increased anterior tilting and internal rotation of the dominant scapula, as well as an increased upward rotation.[59] The gold standard approach to measure scapular movement in the laboratory setting is electromagnetic tracking system.[7,60] In the clinical setting, digital inclinometers are the most common approach to obtain measurements of scapular movements (mainly upward rotation).[61] The test-retest reliability is high in both healthy participants (ICC=0.89 to 0.96)[62,63] as well as those with shoulder pathologies (ICC=0.88).[64] The correlation with electromagnetic systems is high for static measurements (r=0.72 to 0.92), but only moderate for measurements of dynamic scapular motion (r=0.59 to 0.73).[62] Altogether, these findings suggests that intra-rater reliability of digital inclinometers for the measurement of scapular upward rotation position is high, but that more research is needed for inter-rater validation.

2.3 Review of workload measurement in team sports

The fundamental purpose of training in sports is to develop physical abilities and improve performance.[65] This is achieved with the careful exposure to specific stimuli to drive desired adaptations specific to each sport demands.[66] A stimulus slightly higher than a target threshold will launch a cascade of physiological stressors that will stimulate both local and peripheral adaptations to increase future exercise tolerance.[67] A short-term consequence of undergoing this physiological stress is a temporary decrease in performance (fatigue). However, sufficient time for recovery will allow for the return to pre-stimulus levels of performance and even higher (super-compensation).[68] The timely repetition of these overloading phases with adequate rest cumulatively lead to fitness capacity levels much higher than baseline.[69-71]

The physical load that is prescribed to the athletes (external workload, section 2.3.1) will cause stress in both a mechanical and a psychophysiological pathway.[72,73] These external loads can be measured via video analysis and wearable sensors. The actual stress that the athletes perceive (internal load) further depends on their current exercise capacity at the time, which can vary based on many factors including training status, psychological status, health, nutrition, environment, and genetics.[65,67,74,75] Measurements of internal load can be obtained via the analysis of heart rate,[76] wellness questionnaires[77] or an estimate of session rate of perceived exertion.[78] Failure to adapt positively can push the athletes into a state of over-reaching and has been associated with the development of injuries (see section 2.4).[79,80] Therefore, the careful monitoring of sport-specific workload variables[81,82] must be performed and communicated to decision makers to assist with practical changes.[71,74]

Below are descriptions of the methods commonly employed to attempt to quantify the elements of this framework.

2.3.1 Measurement of external loads in team sports

Team sports involve groups of different individuals contributing to group success from diverse positions of the game by performing a multitude of types of movements. Therefore, finding methods to consistently quantify the amount of work they executed comes with several challenges.[83,84] The usual method to derive these values consists of thorough video analysis and manual notation of events.[73] However, this approach is heavily time consuming, depends on available capture volume, and cannot be performed on multiple athletes simultaneously.[85] Instead, wearable devices can be used to estimate these parameters with greater portability and lower costs.[86]

2.3.1.1 Positioning Systems (GPS and LPM)

In a recent systematic review of 407 studies, Benson et al (2020) showed that global positioning system (GPS) transmitters are the most common wearable sports team devices appearing in the monitoring literature, followed by accelerometers and heart rate monitors.[87] GPS technology has been widely used with different football codes (i.e. soccer and rugby) to estimate distances and velocities during training or matches (coefficient of variation 10.9% for 15m sprint).[88,89] Inter-unit reliability remains poor, suggesting that best practice would be to avoid changing the devices between athletes.[85] Furthermore, it has limited use indoors or in areas with structures that can block signal acquisition.[85,88,90-92]

Alternative tracking solutions for indoor sports (i.e. basketball) were developed based on ultra-wide-band radiofrequency localization, altogether called local positioning measurements (LPM).[93,94] These LPM show good validity (1.0-3.5% position error) with moderate to high inter-device reliability (ICC=0.65 to 0.88).[93-95] The level of accuracy of the system decreases when athletes are running at higher speeds (absolute error 2.71km/h), but still outperforms GPS systems.[95,96]

The values of distances and velocities extracted from positional trackers are subsequently transformed into single-value metrics that are easier to plot over time, such as distance, distance per minute, or high-speed running bouts.[71,88] However, using discrete categories instead of continuous variables in the analysis decreases statistical power of the conclusions.[87,97] Ultimately, these metrics do not take into consideration the high energy expense related to rapid changes in direction or the effect of tackles in collision sports.[75]

2.3.1.2 Accelerometers and inertial measurement units

Tackling and jumping impacts represent a major source of load in contact sports such as rugby, American football, and Australian football.[72,98] This has promoted the development of wearable devices that hold embedded accelerometers to quantify these activities.[99] Manufacturers include an array of sensors in their equipment such as GPS transmitters, accelerometers, gyroscopes, magnetometers, and ultra-wide band transmitters.[93] Devices with at least one accelerometer and one gyroscope are called inertial measurement units (IMU). Moreover, devices frequently contain multiple sensors of the same type, calibrated at different thresholds, which can then be blended together by software algorithms to capture a wider range of signals.[96] The ability to sample at much higher frequencies (30-500Hz) makes for more accurate detection of high-speed events compared with GPS.[92] However, the external validity of these wearable sensors is not well documented and shows contradicting results when compared with criterion reference accelerometers or force plate data.[98,100,101] Conversely, the inter-device reliability is consistently high (coefficient of variation of 0.23 to 2.96%).[102-104] These preliminary findings suggest that measurement error is decreasing as the technology of these devices improves rapidly.

The interpretation of accelerometer data is less intuitive for coaches and sports practitioners than that of positioning systems.[72,105] The data derived is often used to calculate a summary metric of instantaneous change of accelerations, with a variable name typical to each developer.[89] This summary variable can be used to compare movement expenditure in both training and match environments.[98] Moreover, accelerations can quantify many aspects of biomechanical load,[89] and algorithms can also use signals from multiple sensors in a wearable device to recognize specific activities.[99] IMU sensors have been used to identify patterns such as throwing motions in cricket (sensitivity 98.1%-99.0% and specificity 74.0%-99.5%)[106] or swim strokes in an aquatic setting (mean error ≤5.1%).[107] However, the algorithms are specific to each sport movement. Consequently, Gastin et al (2014) found that an algorithm developed to identify tackles in rugby failed to produce the same findings when applied to Australian football.[108] The rugby algorithm overestimated the number of collision events, suggesting that the descriptors of tackles used by Australian football coaches may underestimate the true mechanical load experienced by the athletes. Overall, these devices offer many possibilities to quantify external load with more precision, even in environments where other approaches have failed so far.[79,109]

2.3.1.3 Machine learning in load monitoring

Coaches may wish to further use these wearables to count separate types of activities, such as specific strokes in tennis or types of baseball pitches.[110,111] One promising approach to automate these count measurements consists of using machine learning classifiers to draw out patterns from IMU data. There are many tools available to perform these actions, but they all follow general principles of classifying groups of data based on characteristics that emerge from the raw signals (i.e. support vector machine, k-nearest neighbors, regression, etc.). The labels of the groups can be predetermined by the end-user, which is called supervised learning.[112] On the other hand, computers can be left to create their own categories of "similar" data, which is called unsupervised learning. The later requires significantly larger examples to generate reliable groupings (millions of events). In the end, these methods can be used to find consistent and complicated patterns between multiple sensor signals, and could potentially differentiate between similar tasks such as swimming vs throwing in a water polo player.

2.4 Relationship between workload and injuries in team sports

Health care practitioners took interest in these types of investigations more recently as it was proposed that an association can be made between workload and injury risk.[113] This seems biologically plausible when we consider laboratory experiments of tolerance to mechanical stress for tissues such as bone, tendon, muscle and ligaments.[84,114] Therefore, one can expect to find a positive relationship between external workload and injury risk.[115] In 2021, Dalen-Lorentsen et al performed the only randomized control study to evaluate this with 482 young European footballers of both sexes undergoing planned workload prescriptions.[116] They found no significant difference in the relative risk of new injury (RR=1.01, 95%CI=0.91 to 1.12; p=0.84) between their intervention (planned load progression) and control groups. However, injury reporting and adherence to the intervention appear to have been poor, and were not monitored throughout the study. In a cohort study, von Rosen et al (2017) showed that, over the course of one year, increasing workload and training intensity while decreasing sleep made the participants more likely to sustain an injury across 16 sports (n=496, hazard ratio 2.25 [95% CI=1.46 to 3.45], $p<0.01$).[117] Another cohort study with a similar methodology included 679 youth handball players during a 31-week follow-up period.[118] The authors showed that high increases in workload augmented injury risk significantly (HR=1.91; 95%CI=1.00 to 3.70, $p=0.05$). Moreover, even greater increases in injury risk were observed for athletes who also showed reduced external rotational strength (HR=4.0; 95%CI=1.1 to 15.2, $p=0.04$) or scapular dyskinesis (HR=4.8; 95%CI=1.3 to 18.3, $p=0.02$). These study show that the consideration of a series of variables that form a risk profile are more meaningful than attempting to explain injury incidence using a single variable alone.[119] The ability to predict injuries has been likened to determining the path of a hurricane, and although "it is an imperfect science, [it is still] useful enough to guide critical decisions and give estimates".[120]

2.5 Summary of the knowledge gaps

Overall, previous systematic reviews on water polo injuries have focused very specifically on the shoulder area. There is incomplete knowledge about what other injuries occur across the body for water polo players, and even fewer investigations into what risk factors of these injuries might be.

Previous studies have investigated the reliability of shoulder strength measures using hand-held dynamometers and examined validity compared with the gold-standard isokinetic dynamometers.[55,56] These have shown varying levels of agreement in the observations obtained from each device (r=0.28 to 0.96), and these comparisons have not been explored in water polo players. This population is different from regular overhead athletes because they use both arms to swim, yet also have a dominant limb specifically developed for overhead throwing.[18] Therefore, significant asymmetries in strength and flexibility may not coincide with those of other unilateral sports.

Longitudinal studies of risk factors for shoulder injuries in water polo have identified a relationship with baseline shoulder rotator muscle weakness and loss of range of motion. However, the importance of previous injury as a confounder in this relationship is currently unknown, as well as the potential influence of altered scapular upward rotation.

Finally, a method to quantify external training load in water polo without using video analysis is missing. There is no available tool to measure external load in an accessible and reproducible manner that can be tracked over time. Inertial measurement units have not been used in water polo, and no studies of overhead tasks in team sports have attempted to classify activities in such a complex environment.

2.6 Objectives and hypotheses

2.6.1 Chapter 3: Prevalence & mechanisms of injuries in water polo: a systematic review

The starting point to inform the variables that needed to be included in a risk factor study was a thorough review of available research. Thus, the main objective for this chapter was to systematically review the literature on water polo injuries and their risk factors. There was no a priori hypothesis about what this review would yield.

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2.6.2 Chapter 4: Hand-held shoulder strength measures correlate with isokinetic dynamometry in elite water polo players

The objective for this chapter was to estimate inter-trial variability and concurrent validity of hand-held dynamometer shoulder strength measurements compared to isokinetic dynamometer measurements in elite water polo players. Our hypothesis was that the two devices would correlate highly based on previous investigations into other overhead throwing populations.[56]

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2.6.3 Chapter 5: Risk factors for shoulder injuries in water polo: a cohort study

The main objective of this chapter was to estimate whether previous injury, changes in strength, range of motion (ROM) or upward scapular rotation (UR) were related to shoulder injuries in water polo players. Our main hypothesis was that injured players would show lower relative strength values at baseline, lower ratios of external over internal shoulder rotation strength, lower overall range of motion, and lower angles of scapular upward rotation. It was further expected that players with a history of injury would also be more likely to develop new injuries based on findings from other team sports.

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2.6.4 Chapter 6: Automatic Detection of Passing and Shooting in Water Polo Using Machine Learning

Our literature review revealed an absence of a practical method to measure workload in water polo using minimal and portable equipment. Therefore, the objective of this chapter was to develop a method to detect passes and shots in water polo automatically using inertial measurement units (IMU) and machine-learning algorithms. Our hypothesis was that our classifiers would reach a prediction accuracy of at least 90% to identify overhead throwing actions correctly.

This chapter, authored by Félix Croteau, François Thénault, Stéfanie Blain-Moraes, David J Pearsall, David Paradelo and Shawn M Robbins was submitted to the *Journal of Sports Biomechanics,* where it is currently under review.

2.7 Chapter 2 references

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Chapter 3. Prevalence & mechanisms of injuries in water polo: a systematic review

Félix Croteau, Harry Brown, David J Pearsall & Shawn M Robbins

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3.1 Preface

Chapter 2 provided a detailed summary of the hypothesized risk factors for shoulder injuries in water polo. However, many of the studies included lacked a design purposely aimed at observing the relationship between these risk factors and injuries. Furthermore, a narrow focus on shoulder injuries exclusively would prohibit the consideration of other previous injuries acting as a risk factor. Therefore, chapter 3 presents a systematic review of injuries in water polo as well as studies investigating their underlying mechanisms.

3.2 Abstract

Objective: To summarize the information available in the literature on the prevalence of injuries in water polo and injury risk factors.

Methods: Protocol was registered on Open Science Framework. Medline, CINAHL, EMBASE and SportDiscus databases were searched for keywords relating to water polo and injuries on February 3rd 2021. References were searched for additional studies. Only original research papers in English or French were included, and studies without an injured group were excluded. A data extraction file was made based on the Cochrane Collaboration recommendations. Study quality was evaluated with the Newcastle-Ottawa scales for cohorts and a modified version for cross-sectional studies.

Results: The initial search yielded 581 articles, with five more added from reference lists, but only 41 remained after removing duplicates and applying inclusion/exclusion criteria. Thirty-one articles identified the head, fingers and shoulders as the most common sites of injury. Ten articles on mechanism of injury focused mainly on the shoulder, with degenerative changes, posture, scapular alignment, strength, flexibility and overhead shooting kinematics as the main injury risk factors. Publication types included cohort studies, cross-sectional studies, and one case series.

Conclusions: Most traumatic injuries affect the hands and the head from unexpected contact with the ball or opponents. Conversely, training injuries seem to affect mainly the shoulder area. Low level evidence suggests a correlation between shoulder injuries and lack of strength or flexibility as well as large volumes of overhead throwing. Further prospective research is needed to investigate risk factors for other body areas.

Key words: athlete, shoulder, epidemiology, water-polo, swimming, aquatic

3.3 Introduction

Water polo is a sport that consists of two teams of six players and a goalkeeper competing against each other by crossing a pool and shooting the ball into the opponent's net. The men's game is played in a pool area 30m long by 20m wide with a larger and heavier ball (71cm diameter and 450g). The women's game is played in a 25m long by 15-20m wide area[1] with a smaller ball (67cm diameter and 400g).[2] The action of the game requires many short sprinting bouts of swimming totalling upwards of 1000m per game, grappling against opponents, maintaining a vertical position by treading the water and shooting and passing the ball for four quarters of 8 minutes each.[3,4] This makes the athletes both vulnerable to acute traumatic injuries from contact with opponents and to overuse injuries from the large number of repetitions of swimming and overhead throwing.[5,6] Injury surveillance studies in multi-sport events such as the Olympics and FINA World Championships have confirmed that most of the traumatic injuries occur in competition for this sport (>70%) rather than training.[7-13] For this reason, a skilled medical support staff is essential to providing water polo athletes with a safe environment and to treat injured players.[14] A gap remains in identifying the prospective epidemiology of injuries outside of competition in this sport.

Previous studies published on injuries in water polo have outlined the location and types of injuries.[6,15] They have pointed out that common traumatic injuries affect the face and hands[16] whereas overuse injuries most frequently occur in the shoulders and knees.[3,17] However, previous reviews are mainly focused on male elite players, and did not describe injury prevalence across sexes and competition levels. Only two reviews were systematic with their search parameters, and both focused exclusively on shoulder injuries.[6,15] Furthermore, only one review had systematically summarized information from original research investigating shoulder risk factors.[6] Therefore, a systematic review is required to examine the extent of injuries and risk factors in water polo across all anatomical sites. The primary objective of this systematic review was to summarize the information available in the literature on the prevalence of injuries in water polo and associated risk factors.

3.4 Methods

The methodology for this systematic review was based on the PRISMA guidelines,[18] and the data extraction process was informed from the Cochrane Collaboration recommendations.[19] The protocol for this review was registered at Open Science Framework and can be accessed at 10.17605/OSF.IO/2ZHFA.

3.4.1 Information Sources

Four databases were searched on February 3rd 2021 to identify relevant papers: Medline (1946-…), Embase (1947-…), CINAHL complete and SportDiscus complete. The primary keyword strings were “water polo OR waterpolo” and “injury”. Associated medical subheading (MeSH) terms were identified by a professional librarian and included to avoid missing relevant papers. An example of a search strategy for Medline is provided in the Supplemental files (Supplemental Figure A3.2). Reference lists from the review studies were searched manually to identify further relevant articles.

3.4.2 Eligibility Criteria

Peer-reviewed original research articles about water polo players were included if written in French or in English. The subjects were included for both men and women of all available age groups, and of all available competition levels. Articles on musculo-skeletal injuries and concussions were considered for inclusion if they aligned with the definitions of Clarsen et al (2020)[20] for health problems as “any condition that you consider to be a reduction in your normal state of full health […]”. For observational multi-sport studies, data from water polo injuries were included only if they were presented separately from the other sports. Studies with a focus on nutrition, anthropometry, physiology, bone density or woman’s health were excluded. Conference abstracts, review papers and articles without original injury data were excluded. Finally, risk factor studies that did not include an injured group for comparison were excluded.

3.4.3 Study Selection

Two reviewers screened through all of the titles and abstracts to determine if full text articles would be obtained. The first 20 articles were scanned for any disagreements in defining the eligibility criteria. After consensus, each abstract was then screened independently. The authors (FC, SR) met to discuss discrepancies and reached consensus for identification of full-text articles to be read. Next, full-text articles were independently reviewed using a similar process, and consensus was reached between the authors on the final list of articles included for review (see Figure 3.1, detailed exclusion reasons in Supplemental Table A3.5).

3.4.4 Data Extraction

A data extraction form was used to select key information including sample size, gender, participant age, competition level, prevalence, body area and types of injuries, duration of the study, injury definitions as well as confounding measures. Data was collated independently by two authors (FC, HB).

3.4.5 Study Quality Assessment

Study quality was assessed using the Newcastle-Ottawa Scale (NOS) for cohort studies, as well as the Newcastle-Ottawa Scale adapted for Cross-Sectional Studies (supplemental Figures A3.3-A3,4).[21] The NOS for cross-sectional studies was necessary to assess the quality of most risk factor studies, which were cross-sectional in nature as opposed to the designs most common for injury prevalence research (retrospective and prospective surveys or observational cohorts) (Supplemental Table A3.4). The NOS for cohort studies includes eight criteria upon which to assess the study design based on participant selection (four points), comparability of findings (two points), and description of outcomes (three points). The NOS adapted for cross-sectional studies modifies two elements, asking specifically about sample size selection and statistical analysis for a maximum of 10 points. Articles were scored independently by two reviewers (FC, HB) and consensus was reached on scoring without need for a third party.

3.4.6 Statistical Analysis

No statistical analyses were performed to aggregate findings due to a lack of sufficiently similar methods between studies. Findings were grouped by similar populations and ranges of values were provided to summarize the data.

3.5 Results

The initial search yielded a total of 581 articles (Figure 3.1). After removing duplicates, 310 abstracts remained. Five more articles were added from reference lists of review papers. After title and abstract screening, 104 full text articles were evaluated for eligibility. Ultimately 41 articles were included with 31 articles examining the presence of injuries (Table 3.2) and ten studies examining injury risk factors (Table 3.3). Injuries were described in terms of prevalence, or the number of injuries present as a percentage of the number of athletes at one given time.[22] They were also described as period prevalence, or the proportion of athletes in a defined window of time.[22] Other authors described injuries in terms of incidence, which is the number of new cases per total athletes in a fixed window of time.[22] A fourth method is to describe injury rates, where the number of new cases is divided by athlete exposures.[22] Original research describing water polo injury prevalence scored median 8/9 on the NOS for cohorts (range between 6 and 9).[7-14,23-35] For cross-sectional designs, the median modified NOS score was 6/10 (range between 4 and 9).[36-45] Original research investigating risk factors scored 9/9 for both cohort studies[46,47], and a median 7/10 for cross-sectional studies (range between 3 and 10).[2,48-54]

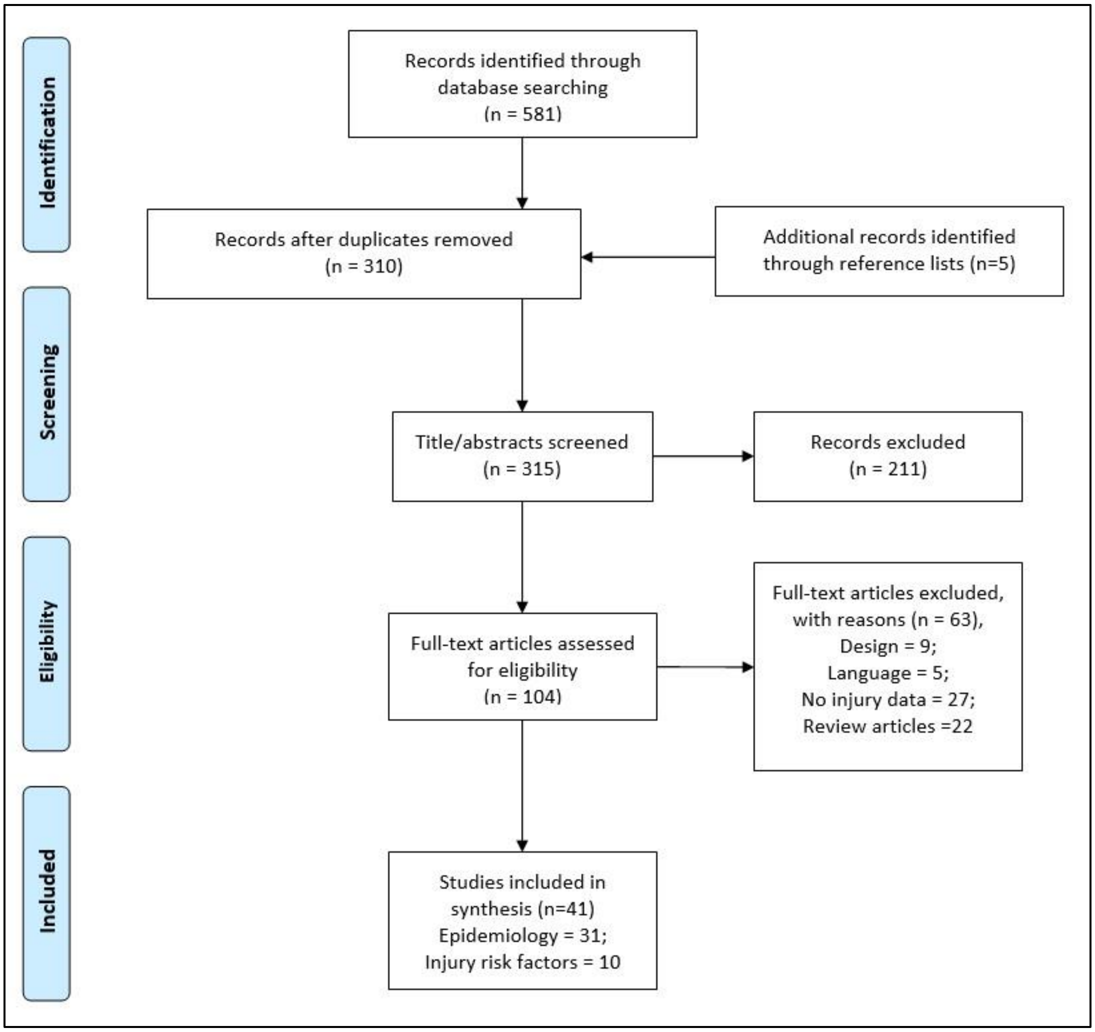

Figure 3.1 Article selection flow diagram

<u>3.5.1 Injury Surveillance Data</u>

Four cohort studies[7-9,13] obtained injury data from implementing surveillance programs during the Olympic Games of 2004 through 2016. At the Athens 2004 Olympics, an injury rate of 63/1000 player*hours was observed for water polo males compared to the overall team sports average of 54/1000 player*hours. In the same period, one single injury was recorded in the female participants.[9] During the 2008 Beijing Olympic Games, 2012 London Olympic Games and 2016 Rio de Janeiro Olympic Games, period prevalence ranged from 9.7%-19.4% for water polo vs 9.6%-12.9% for the overall average for all sports.[8,7,13] Water polo males had higher injury prevalence than females (16.0-22.7% vs 8.7-14.4%).[31] This high period prevalence is echoed in the findings from World Championships 2009 through 2015, where the average was 16.2% (mean age 25±5 years).[12]

During the 1994 *Australian University Games*, 13.1% of collegiate level water polo participants sustained an injury, compared to the overall sports average period prevalence of 19.5%.[14] Three retrospective chart analyses[26,29,33] further investigated collegiate athletes (age 18-22). Macintosh et al (1972) found an injury rate of 141 injuries/1000 player*years in competitive water polo compared to the overall average of 84/1000 player*years in more than twenty other sports (e.g. squash, downhill ski, gymnastics, basketball). Furthermore, water polo represented 11.9% of all injuries recorded over the 18 years of the period analyzed.[29] Sallis et al (2001) found that female collegiate water polo players had an injury rate of 18.4 injuries/100 player*years vs their male counterparts with 7.1/100 player*years. This is much lower than the overall all-sport average for females of 52.5/100 player*years or males of 47.7/100 player*years.[33] Furthermore, Hame et al (2004) found that male players were twice as likely to sustain primary fractures as females (p=0.03).[26] Female players also developed stress fractures, which were not recorded in the male players.

Finally, one cohort study[30] followed a large sample of high school athletes (age 13-18)[25] from 24 different sports over 1 year. It found no injuries in the female water polo players and only two in the boys (5% of participants). This was much lower than the all-sports average period prevalence of 22%.[30]

Table 3.1 Reported period prevalence of water polo injuries per body area in national team athletes

Body part	Period Prevalence			
	Surveys [39]	**Chart review** [23]	**Cohort** [9-11]	**Cross-sectional**
Head and neck	0%	20.2%	20.5% - 53%	n/a
Shoulders	65%	24.1%	6% - 13.6%	n/a
Elbows	0%	11.5%	6% - 18.2%	n/a
Wrist/Hands/Fingers	50%	19.7%	13.6% - 23.1%	n/a
Lumbar spine	0%	2.9%	0% - 11.4%	n/a
Hips/Groin	18%	7.1%	0% - 9.1%	n/a
Knees	24.0%	3.6%	0% - 3.1%	n/a
Ankles/Feet	0%	1.7%	4.5% - 10.8%	n/a

3.5.2 Injury Types and Distribution

3.5.2.1 Head and neck

Given the contact nature of water polo, competition traumatic injuries to the head and face are the most frequent (Table 3.1). Commonly reported injury types across player levels are contusions, lacerations and fractures (0.57/player*year),[44] as well as orofacial or dental (prevalence 21.0%-57.9%)[40,43,45] and ophthalmic injuries (0.45/1000 male player*matches).[35] These contact injuries are the most common reason for consultation in emergency departments (53.6% of all injuries).[25] Perforated ear drums are now less common as a result of improved equipment, more specifically the addition of a hard perforated plastic piece that protects the external ear.[23] Blumenfield et al (2016)[36] and Black et al (2017)[24] both specifically investigated concussions in their studies. The first authors conducted an electronic survey targeting members of USA Water Polo.[24,36] From their 1519 responders, 36% reported a previous concussion (43.5% in females vs 30.8% in males, p=0.01), with an average of 2.1±0.1 episodes during their career. This number was higher for goalkeepers at 47% of respondents with an average of 2.5±0.2 episodes. In a chart review conducted on Canadian university athletes, Black et al (2017)[24] did not find any reported concussion for either male or female water polo athletes. No other author investigated concussions specifically, but Junge (2006) reported that the only injury from female water polo during the 2004 Athens Olympic Games was a concussion.[9]

3.5.2.2 Upper Extremity

Injuries to the hands are also frequent given contact with opponents and the ball (13.6%-23.1% period prevalence,[9-11,23,39] Table 3.1). They include sprains to the finger interphalangeal joints and thumbs, fractures of the metacarpals and phalanges, and a web space tear injury typical to the sport.[44] Outside of competition injuries, the shoulder is commonly cited as the most common site of injury with 6.1%-13.6% period prevalence.[1,3-5,15,16,28,55-59] The types of shoulder injuries in water polo include overuse injuries due to repetitive swimming/throwing, and traumatic due to contact with other players.[6] Overuse syndromes occur such as tendinopathies of the long head of biceps and the rotator cuff muscles, impingement syndromes, thoracic outlet syndrome, labrum degeneration, acromio-clavicular joint degeneration and instability of the gleno-humeral complex.[17] Pathologies from trauma would include labrum tears, rotator cuff tears, dislocations, and fractures of the humerus and scapula.[55] Imaging studies showed that postero-superior impingement syndromes are widely prevalent in symptomatic players.[49] In Klein et al (2014),[2] water polo players showed significant differences in magnetic resonance imaging (MRI) for the infraspinatus (p=0.02), subscapularis (p=0.01) and posterior labrum (p=0.04) on their dominant arm compared to healthy controls. Only eight of the 28 participants had shoulder pain at the time of the study.[2] Furthermore, when Galluccio et al (2017)[48] recently investigated shoulders of professional Italian athletes using dynamic ultrasound, they found that 38 of the 42 participants in their study showed anomalies on imaging, but that only 13 had pain at the time. Finally, injuries to the elbow medial complex (6.0%-18.2% period prevalence[9-11,23,39]) occur because of the overhead throwing motion in water polo.[3]

3.5.2.3 Back and Lower Extremity

Six groups of authors have reported lower back injuries in their samples, with only two including female players,[10,34] with prevalence ranging between 0% and 14.4% (Table 3.1).[10,23,28,34,42,44] Some of the proposed pathologies include degenerative changes to the facet joints from prolonged extension in a swimming posture, the throwing motion or contact from opponents.[1,3,4] Furthermore, the eggbeater swim stroke is a proposed mechanism of injury for common hip pathologies such as impingement issues and tendinopathies (0%-9.1% period prevalence).[16,56,59] The knees are prone to pathologies of the medial compartment or "breaststroker's knee", mainly tibial collateral ligament sprains or tendinopathies of the adductors (0%-6.5% period prevalence).[3,4,16,25,56,59] The ankles and feet were not included in the results from previous reviews, although cohort studies found a prevalence of 4.5%-10.8%.[9-11]

Table 3.2 Epidemiological studies in water polo

Reference	Design	Participants	Outcome	Key findings
Annett & al. (2000)[23]	Retrospective cohort	77 males from national team, mean 20 years old	13 year retrospective chart analysis of documented injuries	Incidence of injuries 1.16/1000hours; 24.1% shoulder, 15.5% face, 14.7% hand, 11.5% elbow; 73.4% acute, 26.6% overuse, 20.5% chronic (>6 weeks)
Black & al. (2017)[24]	Retrospective cohort	28 males and 22 females from collegiate level	3 year retrospective chart analysis of concussions	No injuries recorded
Blumenfeld et al. (2016)[36]	Cross-sectional	895 males and 602 females (and 22 undefined sex) from high school to master's club levels, mean 30 years old	Retrospective survey of life-long concussion injuries	36% overall lifetime prevalence with average 2.14±0.07 episodes; 30.8% males 2.2±0.12 episodes; 45.5% females 2.06±0.08 episodes; 47% goalies with 2.49±0.18 episodes;
Cunningham & Cunningham (1996)[14]	Prospective cohort	382 males and females from collegiate level	Prospective injury surveillance during 1 week	Period prevalence 13.1%;
De Castro-Maqueda & Amar-Cantos (2019)[37]	Cross-sectional	285 males and 202 females from club teams, mean 24±8 years old	Retrospective survey of injury over the last 10 years	10 year prevalence 98.4% shoulder injury, 87% sunburn, 56% groin injury, 23.7% had fracture, 4.2% hypothermia, 2% no injury
Ellapen et al. (2012)[38]	Cross-sectional	100 males of high school level, 15-17 years old	Retrospective survey of pain over the last 12 months	72% prevalence; Incidence 2.49/1000 player*hours; shoulders 51%, vertebral column 18%, upper limb 6%, knee 24%, lower limb 1%
Elliott. J (1993)[39]	Cross-sectional	13 males from national team, mean 28 years old (no injury data for 12 controls)	Retrospective survey of lifetime injuries	Lifetime prevalence 85%; 62% shoulder, 50% hand and finger, 18% groin strain
Engebretsen et al. (2013)[7]	Prospective cohort	156 males and 104 females from national teams	Prospective injury surveillance during 17 days	Period prevalence 13.1% overall; Female prevalence 8.7%; Male prevalence 16%

Forrester (2020)[25]	Retrospective cohort	256 males and 158 females, 73.5% age 13-18 from high school and college	Retrospective chart analysis of emergency department admissions 2000-2019	Head and neck 53.6% of all injuries (56.9% male and 48.1% female), upper extremity 31.1% (29.7% male and 33.6% female), lower extremity 6.5% (6.1% male and 7.2% female); Laceration 19.4% (27.3% male and 6.6% female); strain or sprain 17.8% (14.1% male and 23.8% female); contusion or abrasion 17.6% (17.3% male and 18% female); fracture 13% (14% male and 11.3% female); internal organ 8.4% (4.8% male and 14.3% female but seems to cross-over with concussion); dislocation 5.5% (6.1% male and 4.6% female); concussion 4.8% (6.1% male and 4.6% female); others 13.4%
Galic et al (2018)[40]	Cross-sectional	59 males, mean 12.9±3.2 years old	Retrospective survey of lifetime injuries	Of all respondents, 28.8% had had orofacial injuries, 18.6% dental injuries, only 5.1% wear mouth guards
Goes et al (2020)[41]	Cross-sectional	36 males and 26 females, mean 23.4±5.1 years old and 11.5±6.1 years water polo experience	Retrospective survey of lifetime injuries	Injury counts joint injury 51, muscle injury 43 and tendinopathy 38; Shoulders were 65.8% of tendinopathies, 46.5% of muscle injuries and 31.4% of joint injuries
Gradidge et al. (2014)[42]	Cross-sectional	36 males from high school level, mean 17±1 years old	Retrospective survey of lifetime injuries	Lifetime prevalence 55%; Period prevalence < 1 month 13%; shoulders 25% previous vs 8.3% recent injuries; elbow 11% previous injuries; back 6% previous injuries
Hame et al. (2004)[26]	Retrospective cohort	5900 multi-sport males and females from collegiate level	15 year retrospective chart analysis of fractures	Incidence rate of fractures 0.04-0.05/athlete*year for males vs 0.01-0.02/athlete*year for females; Significant sex difference (p=0.03)
Hams et al (2019)[27]	Retrospective and prospective cohorts	90 males and 128 females from professional league, mean 20.6±3.7 and	Retrospective chart review of self-report shoulder injuries in last 4 years	Incidence 0.65/1000 athlete*exposure; Retrospective 4 year prevalence: 25% shoulder, 17% thoracic and lumbar spine, 15%

		19.3±2.9 years old respectively	AND 3 year prospective injury surveillance	hand/wrist/finger, 10% knee, 9.6% pelvis/hip, 9.2% elbow; Prospective 3 year prevalence: 16% shoulder, 10.5% lumbar, 10.5% hip/groin, 10.5% hand, 9% elbow, 8.3% knee
Hersberger et al. (2012)[43]	Cross-sectional	355 males and 60 females from junior to national level, mean 30 years old	Retrospective survey of lifetime dental injuries	Lifetime prevalence 103 arm and fingers, 72 lip injuries; 87 tooth injuries
Jerolimov & Jagger (1997)[44]	Cross-sectional	102 males from professional league, mean 22±4 years old	Retrospective survey of injuries during professional career	Incidence 0.57/player*year; 48% lips, 13% tongue, 9% cheek, 8% broken tooth;
Junge et al. (2006)[9]	Prospective cohort	Males and females from national teams	Prospective injury surveillance during one month	Period prevalence 9.7%; Incidence 23.8/1000hours; Injury types fracture & dislocation
Junge & al. (2009)[8]	Prospective cohort	259 males and females from national teams	Prospective injury surveillance during one month	Incidence 21/1000 player*matches (95% CI, 11-31); 56% head, 28% upper extremity, 11% trunk, 6% lower extremity
Kim & Park (2020)[28]	Prospective cohort	73 males from national team program, mean 24.4±3.4 years old	Prospective injury surveillance during 8 years	Injury rates 2.06/1000hours (95%CI 1.77-2.34); Proportion of injuries to the shoulder (25.2%), lumbosacral (14.4%), elbow (10.9%) and neck (8.9%) most common; Injury types proportion were joint sprain (31.2%), muscle injury (28.3%) and tendinopathy (14.4%) most common
Macintosh et al. (1972)[29]	Retrospective cohort	Males from collegiate level	17 year retrospective chart analysis	Proportion 11.9% of all injuries from 25 sports; Incidence = 7/1000 player*years for recreational vs 141/1000 player*years competitive
McLain & Reynolds (1989)[30]	Prospective cohort	36 males and 16 females from high school level	Prospective injury surveillance	Period prevalence boys 5.6% vs girls 0%; Incidence 6.34/1000hours

			during one year	
Mountjoy et al. (2010)[10]	Prospective cohort	235 males and 226 females from national teams	Prospective injury surveillance during 14 days	Incidence 89.4/1000 male players and 101.82/1000 female players; 9 head and face, 8arm/elbow, 6 shoulder, 6 wrist/hand, etc.
Mountjoy et al. (2015)[11]	Retrospective cross-sectional and prospective cohort	208 males and 208 females from national teams, mean 25±5 years	4 week retrospective survey and prospective injury surveillance during 14 days	1 month prevalence 41.9% (36.6% male and 46.6% female); Counts during event 65 injuries (33 males and 32 females); Incidence 1.1/100 athlete*days
Mountjoy, Miller & Junge (2019)[31]	Retrospective cohort	1456 males and 1248 females from national teams	Repeated prospective injury surveillance	Period prevalence 14.1% Incidence 56.2 +/- 6.7/1000 hours; 25.6% head, 16.1% hand, 12.7% trunk, 11.3% shoulder
Prien et al. (2017)[12]	Retrospective cross-sectional and prospective cohort	415 males and females from national teams, mean 22±5 years old	4 week retrospective survey and prospective injury surveillance during 14 days	1 month prevalence 19.9%; Prevalence during event 23.1%
Rugg et al. (2019)[32]	Retrospective cohort	40 males and 41 females from collegiate level	7 year retrospective database analysis of UE injuries	Period prevalence 35% upper extremity injuries for males vs 39% for female players; males 22.5% shoulder, 2.5% elbow and 10% wrist and hand; females 19.4% shoulder, 9.8% elbow and 9.8% wrist and hand
Sallis et al. (2001)[33]	Retrospective cohort	Males and females from collegiate level, age 18-22 years old	9 year retrospective database analysis	Incidence 18.38/100 player*years(females) vs 7.10/100 player*years(males); Incidence /100player*years by area: shoulders 8.09(female) vs 3.4(male), knee 2.94(female) vs 0.93(male)
Soligard et al. (2017)[13]	Prospective cohort	154 males and 104 females from national teams	Prospective injury surveillance during 17 days	Period prevalence 19%

Toohey et al (2019)[34]	Prospective cohort	6 males and 36 females from national team, mean male 19.9±3.4 and 20.8±4.1 respectively	Prospective injury surveillance over 8 months	Injury counts 74 ; 23% shoulder, 16.2% elbow, 13.5% lumbar; 21.6% impingement, 18.2% sprain, 16.2% strain
Youn et al. (2008)[35]	Retrospective cohort	Males and females from collegiate level, age 18-22 years old	Retrospective chart analysis of ocular injuries	Incidence 0.45/1000 male player*matches vs 0/1000 female player*matches
Zamora-Olave et al. (2018)[45]	Cross-sectional	224 males and 123 females from club teams, 10 years old to senior	Retrospective survey of orofacial injuries over the last 12 months	Period prevalence 57.9%

3.5.3 Risk factors for injury

Nine of the ten studies of risk factors with injured participants focused on the shoulder, with seven cross-sectional[2,48-52,54] and two longitudinal cohort designs.[46,47] Half of these studies included female participants in their sample.[46,47,49,50,53] Cohort studies including both sexes have consistently reported more injuries occurring during competition than during training in national team players.[7,8,10,11,13,31] Junge et al (2006) estimated that two thirds of injuries during the Olympic Games were suffered as a consequence of foul play, such as punching or kicking.[9]

3.5.3.1 Training volume

Volume of training is a major variable amongst external risk factors. Wheeler et al (2013)[53] published the only study to analyze the relationship between overhead throwing volume and shoulder soreness/pain. They counted the number of throws per player during Australian national team selection camps by filming and following seven female players from the senior squad. At the same time, daily questionnaires were filled to rate shoulder soreness on a 10 point numerical rating scale. Using linear regression, their model suggested that 74% of shoulder soreness was attributable to shooting quantity ($R^2 = 0.743$, $p=0.01$), with shorter breaks between shots also being a significant factor ($p=0.03$). They also found more soreness during the simulated competition week than during the skills-based selection camp ($p<0.01$).

3.5.3.2 Scapular kinematics

In 2014, Mukhtyar et al measured the scapular position of 30 water polo athletes before and after an intense practice.[52] They selected participants with diagnosed shoulder impingement (n=14) and selected a comparison group with no known shoulder pathologies or pain (n=16). At baseline, they found no differences between groups. However, after the training session, the group with shoulder impingement showed significantly decreased values for scapular abduction and upward rotation (rotary index 0.60cm±0.10 vs 0.24cm±0.07, $p<0.05$).

3.5.3.3 Mobility and asymmetries

Two studies[39,46] investigated the relationship between shoulder flexibility and injury or pain. In 1993, Elliott investigated the relation between flexibility and shoulder pain in 13 male athletes from the English national water polo team and compared their findings with a control group of 12 healthy volunteers.[39] They found that water polo players showed increased flexion (182±15° vs 158±11°, $p<0.01$) and decreased medial rotation of their dominant arm vs controls (46±12° vs 55±16°). However, they found no statistical correlations between shoulder pain and mobility differences. Recently, Hams et al (2019) investigated the relationship between flexibility measures at baseline and prospective injury in a group of 76 elite water polo players in Australia.[46] They found that injured athletes showed lower total range of motion of the dominant shoulder at baseline vs the uninjured players (mean difference = 7.5°, odds ratio (OR) 3.6, 95% confidence interval (CI) 0.8 to 16.0).

3.5.3.4 Shoulder strength and muscle imbalances

Although other authors have published normative values on shoulder strength in water polo players,[60-63] only one group has included an injured sample in their studies.[46,47] Hams et al (2019) assessed shoulder strength in 15 national-level water polo athletes using a hand-held dynamometer and standardized measurement protocol. Players were followed-up over six months and comparison was made at the end of the study between the players that developed prospective injuries vs those that did not. The injured group showed 16.8% lower mean peak strength vs body weight in shoulder internal rotation on average (OR 13.8, 95%CI 2.2 to 88.0) and 12.5% less external rotation (OR 5.2, 95%CI 1.0 to 27.9). However, no group differences emerged in external rotation/internal rotation strength ratios.[47]

3.5.3.5 The water polo overhead throw technique

Whiting et al (1985) performed 3D video analysis cross-sectionally of six healthy and seven injured members (rotator cuff tendinitis) of the US senior national team.[54] The injured group showed significantly longer throw duration (241±11 msec vs 227±9 msec, $p<0.01$), slower peak angular velocity (1104±72°/sec vs 1182±45°/sec, $p<0.01$) and slower angular velocity at release (652±51°/sec vs 738±41°/sec, $p<0.01$).

More recently, Melchiorri et al (2011)[51] conducted a study on the water polo penalty throw with a larger sample of national team males (17 with shoulder injuries and 36 healthy). They found no significant differences between the injured and non-injured groups in ball speed at release (overall mean 24.15m/s), elbow angle at release (overall mean 150±8°), shoulder angle at release (overall mean 141±6°), head height (overall mean 48±11cm) or throwing time (overall mean 151±27ms). However, trunk rotation time was significantly higher for the injured than for the healthy subjects (140±18ms vs 110±17ms, $p<0.05$).[51]

3.5.3.6 Lower Extremity

Langner et al (2020)[50] published the only investigation of the lower extremity. In their population of 13 water polo players with decreased hip-related quality of life, they found signs on magnetic resonance imaging of femoro-acetabular impingement and labral tears were present in 8/13 participants. CAM morphology was present in 69.2% of water polo players, and 30.8% showed pincer morphology.[50] The authors propose that the motion of treading water is responsible for these changes.

Table 3.3 Publications on risk factors

Reference	Participants	Design	Outcome	Key findings
Galluccio & al. (2017)[48]	42 males from professional league	Cross-sectional	Pain questionnaire as part of cross-sectional study	Shoulder pain prevalence 31.0%; Dominant shoulder SST tear 21.4%; SSC tear 7.1%; LHB tear 0%; SST tendinopathy 19.1%; SSC tendinopathy 2.4%; LHB tendinopathy 16.7%; impingement 21.4%; sub-acromial bursitis 16.7%; SLAP tear 4.8%
Giombini & al. (1997)[49]	7 males and 4 females from national team, mean 24 years old	Case series	Magnetic Resonance Imaging investigation of shoulder area	Postero-superior labral damage 11/11; increased signal intensity on the undersurface of the RC 11/11; postero-superior glenoid impingement of SST 11/11
Hams et al. (2019)[46]	28 males and 48 females from national team, mean 20±3 years old	Cohort	Shoulder range of motion measured with goniometry and shoulder rotation strength measured with hand-held dynamometer	Prospectively injured athletes showed significantly lower total ROM ($p=0.05$), lower strength of ER ($p=0.03$) and IR ($p<0.03$)

Hams et al. (2019)[47]	9 males and 6 females from national team, mean 18±1 years old	Cohort	Shoulder internal (IR) and external rotation (ER) strength measured with hand-held dynamometer	Prospectively injured athletes showed significantly lower ER and IR strength ($p \leq 0.01$) but no differences in ER/IR ratios; Healthy IR 14.57kgF vs 9.26kgF, Healthy ER 10.97kgF vs 7.35kgF, healthy ratios ER/IR 0.77 vs 0.81 (at 90-90 position); Healthy IR 19.62 vs 14.56kgF, healthy ER 14.50 vs 10.29kgF, ER/IR ratio 0.75 vs 0.72 (in neutral)
Klein et al. (2014)[2]	28 males from national league, mean 24 years old	Cross-sectional	Magnetic Resonance Imaging investigation of shoulder area	Dominant strength SST 12.2±2.9kgF, ISP 9.9±2.5kgF, SSC 11.6±2.3kgF; MRI positive findings: SSP 15/28 shoulders, SSC 15/28, ISP 12/28, labrum cranial 10/28 vs posterior 15/28 vs anterior 6/28, cysts 6/28, LHB 17/28, cartilage 9/28, AC changes 7/28, bursitis 25/28
Langner et al. (2020)[50]	5 male and 8 female college level, age 18-23	Cross-sectional	Magnetic Resonance Imaging investigation of the hips	Abnormal alpha 9/16 female vs 9/10 male; abnormal lateral edge-center angle 5/16 female vs 3/10 female; labral tears 8/16 female vs 8/10 male
Melchiorri et al. (2011)[51]	53 males from national team, mean 24±3 years old, 17 injured	Cross-sectional	Video analysis to estimate joint angles and ball throwing speed	Ball speed injured 23.9±1.7m/s vs 24.6±2.2m/s; elbow angle release injured 147±8° vs 148±6°; throw time injured 150.6±28.2ms vs 149.4±29.6ms; shoulder angle injured 144±6° vs 138±5°; head height injured 55.1±8.7cm vs 37.4±13.1cm; trunk rotation time injured 140±18ms vs 110±17ms
Mukhtyar et al. (2014)[52]	30 participants from national league, 17-35 years old, 14 injured	Cross-sectional	Static scapular alignment measured in neural and end range shoulder elevation	Rotary index healthy at 0° position 0.3975 vs 0.1379 ($p<0.01$); healthy at 45° position 0.2781 vs 0.2064 ($p=0.04$); healthy at 90° position 0.3144 vs 0.2743 ($p=0.13$)
Wheeler et al. (2013)[53]	7 females from national team, mean 23 years old	Cross-sectional	Video analysis of practices and daily questionnaire of shoulder soreness	74% of shoulder soreness was explained by shooting volume and significant association also with decreased rest between reps; Volume of shots per day 29±5 for squad selection vs 55±21 for team practices; more soreness in squad selection VAS (3.8±1.0) vs team practices VAS 2.9±0.4, $p<0.05$); rest between shots in squad selection 274±183s vs team practice 148±50s
Whiting et al. (1985)[54]	13 males from national team, mean 27±3	Cross-sectional	Three-dimensional video analysis with orthogonal views to	Throw duration healthy 227±9ms vs 241±11ms; peak angular velocity healthy 1182±45°/s vs 1104±72°/s;

	years old, 7 injured		estimate joint angles and ball release speed	elbow angle at release healthy 155±2° vs 155±3°; ball velocity healthy 19.3±0.5m/s vs 19.9±0.7m/s

AC = acromio-clavicular, ER = external rotation, IR = internal rotation, ISP = infraspinatus, LHB = long head of biceps, MRI = magnetic resonance imaging, RC = rotator cuff, ROM = range of motion, SLAP tear = superior longitudinal antero-posterior tear, SSC = subscapularis, SST = supraspinatus, VAS = visual analog scale

3.6 Discussion

The search yielded 31 articles focused on injury prevalence in water polo (including twelve observational cohorts) and ten articles on risk factors. The populations observed include adolescents, collegiate, national team and professional players. Water polo injury prevalence is high, with the highest values found in national team players (16.2% to 19.4%),[13,31] less in collegiate players (13.1%),[14] and lowest in adolescents (5.6%).[30] This trend may reflect the higher intensity and illegal physical contact that is proportional to higher competition levels. Rule changes will be necessary in order to decrease these foul play injuries, as evidence shows that they are still largely present in this sport at the international level.[31] Most injuries occur in competition situations, and affect predominantly the face and hands with lacerations, contusions and sprains/strains.[25] Concussion incidence should be high given the predominance of head contacts, but current evidence is conflicting. Available literature suggests that shoulder injuries are the primary overuse injury in this sport,[27] which is reflected by the available risk factor studies identified in this review. The primary causes of shoulder injuries investigated thus far are a lack of flexibility and weakness of the rotator cuff muscles,[46] as well as larger volumes of overhead throwing repetitions.[53] Surveillance data in teenagers (13-18) further suggests that most complaints are overuse rather than traumatic in nature.[38,42] This suggests that the process of musculoskeletal adaptations to the demands of water polo may be a source of soreness in this age group in particular. Optimal training methods and planning must be sought to promote wellness and performance most notably in younger players.[64]

3.6.1 Sex comparisons

During the 2009 and 2013 FINA World Championships, females suffered very similar of injuries to the male participants. Despite using similar methodology, surveillance data from the Olympics shows higher rates for male players.[9,13] Furthermore, male players were more likely to have time-loss injuries and more severe conditions.[31] Although the number of teams at the World Championships is equal for men and women, there are four less female teams at the Olympics.[8] Given that the response rates from the participating teams are inconsistent in these events,[31] the increased number of male teams may be the reason for higher recorded injury rates.

For collegiate athletes, Sallis et al (2001) found that females had nearly three times greater injury incidence rates, most significantly for the shoulder.[33] This study scored a perfect 9/9 on the NOS quality assessment, and its findings suggest a difference in exposures for the female players. This may be the consequence of lesser quality workload management for the females, or rather an under-representation of overuse injuries in male players. Including a surveillance method such as the Oslo Sports Trauma Questionnaire can be more sensitive to identify these injuries that do not require medical consultations.[20] Concussion findings in this population are inconsistent, but survey data suggests that females are more susceptible to this injury.[24,36] This is consistent with previous reviews[65,66] investigating sex differences in concussion incidence in sport, but authors have not determined whether this is the consequence of reporting bias or a true increased risk for females.

3.6.2 Player position

Limited information is available to compare injuries at different player positions. Nevertheless, Cecchi et al (2019) demonstrated that players in the "center" role receive the most hits to the head, but failed to record any concussions during their three-season study in collegiate males.[67] This is the direct consequence of their role in attempting to maintain a position in front of the opponent's net as they are wrestled out of their spot. Accidental blows from elbows or punching can occur during these grappling periods. This is also supported by surveillance data from Croatian male professional leagues, where players in the center had more facial injuries on average (5.5/player).[44] Goalkeepers are also prone to injury from contact with the ball, rather than from other players.[36] In particular, balls rebounding on the posts of the net are prone to hit the goalkeepers on the head and are related to the higher incidence of concussions at this position.[36] Further research is needed to investigate these position-specific patterns, given that players on the perimeter swim longer distances in matches,[6] and one can expect more overhead throwing injuries in this subgroup.

3.6.3 Injury Risk Factors

Shoulders appear to be the most common area of overuse injuries in water polo players,[27,28] and original research on risk factors has focused extensively on this joint. Potential risk factors investigated include throwing volumes, strength, flexibility, and proprioception and scapular alignment. The mechanical demands of the swimming, throwing and grappling nature of the sport appear to lead to predictable anatomical adaptations.[48,49] Although these changes on imaging are usually considered pathological, they did not correlate with clinical symptoms of shoulder pain in this group.[48] Currently, one single study was designed prospectively to evaluate the roles of flexibility and strength as risk factors in water polo.[46] They concluded that insufficient strength and lack of flexibility are related to injury, which supports previous hypotheses.[60-63,68] However, strength ratios between external and internal rotators of the shoulder were not statistically related to injury in their sample. Perhaps this is the result of testing shoulder strength in isometric contractions only, which does not mimic the action of the rotator cuff during overhead throwing.[37] When available, isokinetic dynamometry can provide more information about strength profiles for clinicians working with water polo players.

Preliminary findings from studies on overhead throwing kinematics show conflicting results. However, both research groups have observed an increased duration of the throwing action in injured players.[51,54] This suggests a decreased efficiency at coordinating a complex task such as throwing a ball while maintaining an upright position in the water. This can be the result of faulty technique, leading to increased stress on the shoulder.[69] Furthermore, the same patterns of inadequate throwing can lead to distraction injuries to the medial elbow complex, compression injuries to the lateral complex and to the olecranon and its fossa.[5] The eggbeater motion required to stay upright could also promote overuse syndromes such as tendinopathy of the dorsiflexors, periostitis and possibly compartment syndrome. Presently, no authors have reported the specific types of foot or ankle injuries seen in water polo players, and analyses of lower body risk factors are rare.[70,71]

3.6.4 Recommendations

In order for future research to allow for a meta-analysis of injuries in water polo, authors must provide unambiguous definitions of injuries. Injury surveillance studies that scored lowest on the NOS failed to ascertain exposure and outcome distinctly. Thus, the injury incidence rates and prevalence should reflect data collected prospectively over long periods (>6 months) on players of both sexes, with a transparent methodology to avoid recall bias.[72] Authors should implement tools that are more sensitive to monitor overuse injuries such as the Oslo Sports Trauma Research Center questionnaire.[73] Consistency is important in methods, as the increasing rates of injury prevalence at major games (World Championships and Olympic Games) is likely a reflection of improved data collection alone.[31]

On the other hand, risk factor studies with lower quality scores rarely presented sample size calculations, and were limited to cross-sectional designs in all but one research group. A prospective design is crucial to understand the causal relationship between these variables and injury incidence.[46,74] Studies including younger players are lacking to understand the specific mechanisms of injury in this age group. Including specific estimates of training volume as done by Wheeler et al (2013)[53] would add a needed layer of interpretation to the complex etiology of injuries in water polo.[22]

3.7 Conclusion

Gaps remain in the water polo injuries literature, with a large body of narrative reviews and only two systematic reviews focusing exclusively on shoulder injuries. Although data is currently available to provide insight into these injuries for national team level players, limited information can be found for younger age groups. Information is also inconclusive regarding sex comparisons. The current evidence suggests that shoulders are the source of most overuse injuries, and as such the bulk of risk factor investigations have focused on this area. Future research should include a prospective design to investigate the causal relationship between these risk factors and injuries.

Clinicians working with water polo players should be aware that monitoring shoulder strength and flexibility may provide insights about players at higher risk of injury. Programs to maintain adequate range of motion and increase strength should be favored throughout the year. Younger players may experience overuse injuries as a consequence of the adaptation process to the musculoskeletal demands of the sport. Consequently, careful planning of progressive exposure is necessary as well as targeted development programs in this subgroup. Finally, available evidence shows that abnormal imaging findings are common in this population, both for the shoulder and hip areas. Clinicians should confirm that symptoms expressed by the patients match with the observed imaging to construct their rehabilitation plans.

3.8 Acknowledgements

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Chapter 4. Hand-held shoulder strength measures correlate with isokinetic dynamometry in elite water polo players

Félix Croteau, Shawn M Robbins, David J Pearsall

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4.1 Preface

In chapter 2, strength was identified as a risk factor for shoulder injuries in water polo. A small cohort group was evaluated using hand-held dynamometry, but this is not the gold-standard method to assess this characteristic. Furthermore, previous publications of shoulder strength in water polo was performed with isokinetic dynamometers. Therefore, a gap exists to allow for the comparison of healthy vs injured players using dynamometers. Chapter 4 shows the results of a study comparing the reliability and correlation of measures between hand-held and isokinetic dynamometers in water polo players.

4.2 Abstract

Context*:* Previous authors suggest lack of strength is an important risk factor for injuries in water polo. Hand-held dynamometers have potential as a clinical tool to measure strength, but they have not been validated in water polo players.

Objective*:* The purpose of this study was to estimate inter-trial variability and concurrent validity of hand-held dynamometer shoulder strength measurements in elite water polo players.

Methods*:* 19 male and 20 female elite water polo players performed isometric external (ER) and internal (IR) rotation strength test against a hand-held dynamometer bilaterally in supine with the shoulder in a 90-90 position. Additionally, concentric IR and ER was captured at $90^{o}s^{-1}$ with an isokinetic dynamometer, and torque values were determined near the 90-90 position.

Main Outcome Measures*:* Spearman's correlation coefficients were calculated for ER torque, IR torque and ER/IR ratios between the devices. Two-way mixed model intra-class correlations (ICC) were used to assess inter-trial variability.

Results*:* Correlation between the devices were strong to very strong (rho=0.65 to 0.82, $p<0.01$) for absolute IR and ER but low for ER/IR ratios (rho=0.29, p=0.07). There was less agreement at higher torque values. Inter-trial variability was low with ICC values 0.88 to 0.93, $p<0.05$.

Conclusions*:* These results showed that hand-held dynamometers are adequate clinical alternatives to measure absolute shoulder strength in water polo players. Stronger players may require stronger evaluators to resist the player's push and obtain reliable results.

Key words: dynamometer, strength, athlete, aquatic

4.3 Introduction

Injury surveillance at Olympic Games ranks water polo as the aquatic discipline with the highest rates of injuries (19.4% injury rates at the 2016 Rio Olympics).[1] Prospective studies have shown that the shoulder is the most commonly reported site of overuse pain.[2] Strength factors that relate to shoulder injuries in water polo include strength deficits in internal (IR) or external rotation (ER), as well as low ratios of ER/IR.[3] The gold standard tools to assess strength are isokinetic dynamometers, but they are costly, time-consuming and require trained technicians to operate. Hand-held dynamometers are an alternative tool for shoulder strength IR and ER assessments in healthy adults with good inter-rater reliability (intra-class correlation (ICC) 0.89 to 0.97, standard error of measurement (SEM) 4.15-13.57N, minimal detectable change (MDC) 11.28-31.18N), but evaluator strength and experience can potentially induce systematic bias.[4,5] Thus, the main objective was to assess the inter-trial variability of hand-held dynamometer for measuring shoulder strength and determine its concurrent validity against an isokinetic measurement in elite water polo players. A secondary objective was to compare these findings between males and females.

4.4 Methods

4.4.1 Participants

Participants were 19 male and 20 female elite water polo players greater than 18 years of age (mean 23.1±3.6 years), and members of the Canadian national water polo teams who train in a full-time program (Table 4.1). Players with an injury resulting in an inability to fully participate in all regular unmodified training were excluded. All eligible participants at our centre were included to maximize sample size. All participants signed a consent form. The study was approved by the McGill University Ethics Institutional Review Board (study A01-M01-20A).

4.4.2 Procedures

All strength measurements were taken in the afternoon before training sessions. Isometric internal and external rotation strength was measured bilaterally with a hand-held dynamometer (MEDUP®, 5000 N full scale, 2000 Hz sampling rate) with the patients lying in supine with the shoulder at 90° of abduction and external rotation, and the elbow flexed to 90° (Figure 4.1). The evaluator (FC) was a 95kg male physiotherapist with nine years of clinical experience. The evaluator was standing and the pressure sensor aligned with the distal radio-ulnar joint line. Instructions to participants were, “Try to hold this position and keep me from moving you”. Three consecutive measurements were taken to resist abduction/external rotation, with a 10 seconds rest in between, followed by three consecutive measurements of adduction/internal rotation. The participants received verbal encouragement throughout. The sequence was then repeated for the opposite arm.

After a 10 minute break, participants were evaluated in the same position using a CON-TREX® isokinetic dynamometer (CON-TREX MJ; CMV AG, Dübendorf, Switzerland) with a protocol of $90°s^{-1}$ concentric/concentric contractions with a maximum torque tolerance of 250 Nm sampled at 4000 Hz (Figure 4.2). Eccentric protocols were avoided to minimise impact on training readiness because they induce the most muscle soreness.[6] A warm-up of five [submaximal] repetitions was done concentrically for the shoulder internal and external rotators. After a one-minute break, testing followed for one set of three consecutive repetitions[7]. The raw signal was gravity corrected automatically as per CON-TREX® software, then a custom *RStudio* script filtered the data to maintain only the values measured within the target isokinetic load range at the target of $90° \pm 0.5°s^{-1}$. This removes values obtained close to the end of range where the device must slow down, come to a stop, and change direction. Next, the data was filtered to select only the data measured approximately in the same position as the isometric procedure (neutral ER ± 5°). This was done to avoid introducing bias from differences in length-tension relationships obtained in other angles.[8] The peak value was identified as the maximum value recorded within this filtered subset.

4.4.3 Statistical Analyses

Mean values of isometric external and internal rotation strength from the hand-held dynamometer were calculated from the three trials. Values were recorded on the device in foot pounds and converted to Newtons. The value was multiplied by the estimated forearm length in meters using formulas based on body height from Mohanty et al (2013) to obtain torque (Kg·F·m).[9] Isometric ER/IR ratios were calculated by diving the average external torque by the average internal torque. Peak values of external and internal rotation concentric strength were obtained by identifying the single maximum overall values in the filtered data from the isokinetic device as per Edouard et al (2019).[8] Relative strength was obtained by dividing the mean absolute strength of each athlete by their body [weight].

Shapiro-Wilk tests confirmed that the data were not normally distributed. Thus, Spearman rank correlation test was used to determine the relationship between isometric and isokinetic strength results using previous criteria (0-0.19 very weak, 0.20-0.39 weak, 0.40-0.59 moderate, 0.60-0.79 strong and 0.80-1.00 very strong).[10] Bland-Altman plots were used to measure agreement throughout the range of values obtained, including calculating limits of agreement with 95% confidence intervals.[11] Kendall's tau statistic was applied to verify heteroscedasticity (whether the agreement between measures changes as the values increase), using a cut-off value of $\tau>0.1$[12]. Same-day inter-trial variability was analysed using ICC model 3,1 (two-way mixed model).[4] Standard error of measurement (SEM) was calculated by $SD\ x\ 1\ \sqrt{1\text{-}ICC}$. Minimal detectable change (MDC) was calculated as $SEM\ x\ 1.96\ x\ \sqrt{2}$. Wilcoxon rank sum test evaluated differences between sexes. Effect size were calculated using Hedge's correction *g* given the small sample size and presented with 95% confidence intervals.

Figure 4.1 Hand-held device setup*:* Medup™ hand-held device placed on the ventral aspect of the wrist to test isometric strength in internal rotation with the participant in supine in 90-90 position.

Figure 4.2 Isokinetic dynamometer setup*:* Participant in supine on the Contrex™ device to measure isokinetic shoulder internal and external rotation in the 90-90 position

4.5 Results

External and internal rotation strength values showed strong to very strong[10] correlation (rho=0.65–0.82, p<0.01) between the hand-held and isokinetic dynamometers. However, there was low correlation between ER/IR ratios measured by the two devices (rho=0.26-0.29, p=0.07-0.11). Bland-Altman plots show heteroscedasticity for IR and ER: as measurement values increase, the difference between the devices increases as evidenced by the asymmetric funnel shape (Figure 4.3 and Figure 4.4, Supplemental). Kendall's Tau statistic confirms this trend (τ=0.444-0.489), and taking the log values of the variables did not change this trend. Bias values were all positive, indicating that the isokinetic values were higher than matched values on the hand-held device (Table 4.3). Upper and lower limits of agreement are indicated on the figures with their 95% confidence intervals. Inter-trial variability for the hand-held dynamometer measurements was good to excellent (ICC = 0.88 to 0.93, p<0.05, Table 4.2).

Comparisons between male and female participants showed all absolute and relative strength values to be significantly higher for male participants, with moderate to large effect sizes (Table 4.4, Supplemental). Strength ratios were not significantly different between sexes.

Table 4.1 Demographic characteristics of participants

Variable		Males (n=19)	Females (n=20)
Age, years (SD)		22 (3)	24 (4)
BMI, kg/m^2 (SD)		25.8 (2.6)	24.2 (2.6)
Hand dominance	Right	19	18
	Left	0	2
Player position	Goalie	3	4
	Set	7	6
	Driver	9	10
Training setting	National center	10	3
	Professional	8	8
	College (NCAA)	1	9

BMI = body mass index, NCAA = National Collegiate Athletic Association

Table 4.2 Inter-trial variability and concurrent validity of the hand-held dynamometer

Variable [95%CI]	Dominant ER	Dominant IR	Non-dominant ER	Non-dominant IR	Dominant ER/IR	Non-dominant ER/IR
ICC (3,1)	0.90 [0.84,0.94]	0.91 [0.86,0.95]	0.88 [0.80,0.93]	0.93 [0.89,0.96]	…	…
SEM (Kg·F)	6.6 [5.1,8.4]	8.3 [6.2,10.3]	6.9 [5.2,8.9]	7.7 [6.2,10.9]	…	…
MDC (Kg·F)	8.3 [6.5,10.6]	10.4 [7.8,13.0]	8.6 [6.6,11.1]	9.7 [8.1,13.7]	…	…
Spearman rho	0.65 [0.42,0.80]	0.82 [0.68,0.90]	0.77 [0.58,0.87]	0.71 [0.51,0.84]	0.29 [-0.03,0.56]	0.26 [-0.06,0.53]

ICC = intra-class correlation, SEM = standard error of measurement, MDC = minimal detectable change, ER = external rotation, IR = internal rotation

Table 4.3 Bias and limits of agreement between devices

Variable [95%CI]	Dominant ER	Dominant IR	Non-dominant ER	Non-dominant IR	Dominant ER/IR	Non-dominant ER/IR
Bias	0.17 [0.13, 0.20]	0.23 [0.20, 0.27]	0.17 [0.14, 0.20]	0.21 [0.17, 0.25]	-0.08 [-0.13, -0.03]	-0.03 [-0.07, 0.02]
Upper LoA	0.36 [0.30, 0.41]	0.45 [0.39, 0.51]	0.35 [0.30, 0.40]	0.45 [0.38, 0.52]	0.22 [0.13, 0.30]	0.25 [0.17, 0.33]
Lower LoA	-0.03 [-0.08, 0.03]	0.02 [-0.04, 0.08]	-0.01 [-0.06, 0.05]	-0.03 [-0.09, 0.04]	-0.38 [-0.47, -0.29]	-0.30 [-0.38,-0.22]
Kendall Tau	0.489	0.444	0.559	0.567	-0.175	0.090

LoA = limit of agreement, ER = external rotation, IR = internal rotation

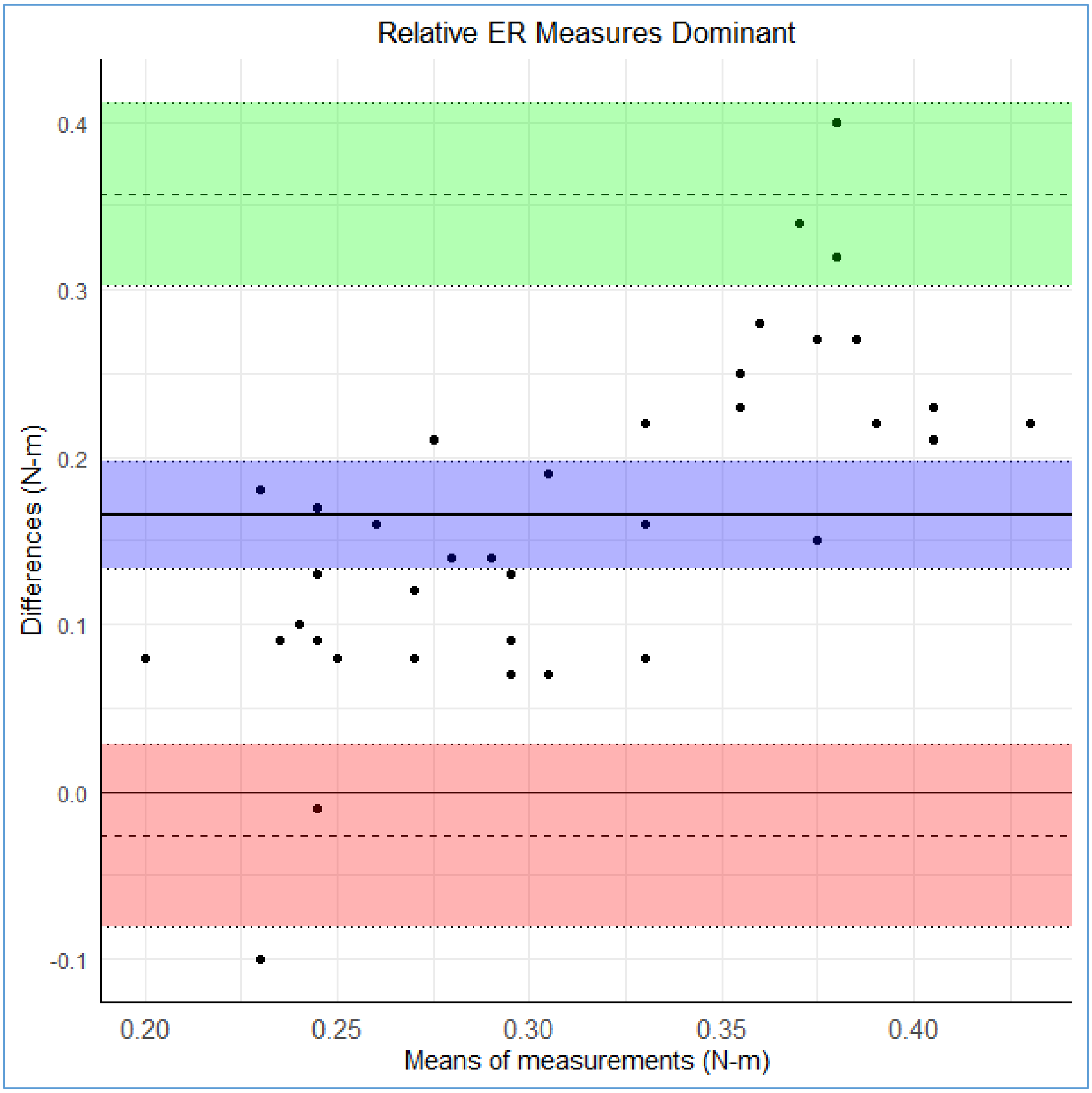

Figure 4.3 Bland-Altman plot showing the relationship between the difference vs the mean of measures of shoulder external rotation. The bias line is in the center (0.17, 95%CI 0.13 to 0.20), with the upper (0.36, 95%CI 0.30 to 0.41) and lower limits of agreement (-0.03, 95%CI -0.08 to 0.03) with their 95% confidence intervals in green and red respectively (see Table 4.3). The shape of the plot shows that as the strength values increase, so does the difference between the two methods.

4.6 Discussion

The hand-held dynamometer in this study showed very good inter-trial variability and concurrent validity with the isokinetic dynamometer (rho=0.65 to 0.82) for measuring internal and external rotation shoulder strength in water polo players, consistent with the general population [4]. This suggests that hand-held dynamometers can be used to measure shoulder strength in water polo players although modifications to the protocol may be required for stronger players.

The ICC is a relative reliability measure and current results showed acceptable reliability (>0.70) (or low inter-trial variability) (ICC=0.88 to 0.93). These results are comparable to those obtained by Cools et al (2016) who conducted a study of 201 overhead throwing athletes with the same testing position (ICC=0.86 to 0.92).[13] Furthermore, measures of absolute reliability[8] such as the SEM shows that the hand-held dynamometer used has an error of 6.6 to 8.3Kg·F. The MDC is a measure that suggests that between trial differences of at least 8.3 to 10.4Kg·F must be measured for the evaluator to conclude that change has occurred. Altogether, these findings show that there is low same-day variability with the hand-held device, which makes it an acceptable alternative for testing shoulder strength in water polo players in a clinical setting.

Overall, agreement between hand-held and isokinetic dynamometers was strong, and thus the hand-held devices can be used clinically when the later are unavailable. However, ER/IR ratios had low, non-significant correlations. This may be the consequence of small variability in ER/IR ratios compared to absolute strength measures in this small sample. ER/IR ratios have shown no correlation with injury in previous studies (Figure A4.5, Supplemental).[3] Bland-Altman plots show increasing disagreement between the two testing devices as torque values increase, which is often observed for ratio variables[12]. This might indicate hand-held dynamometer strength values are less valid at higher values, and hence other testing protocols such as stabilising the elbow of the participants must be explored. Otherwise, values recorded with the isokinetic device may be less precise when getting closer to the maximum torque allowed for the test.

Sex comparisons demonstrated that males were significantly stronger than females in both ER and IR muscle groups. However, there were no significant ER/IR ratio differences between sexes. These findings are aligned with other previous studies.[3,13] Therefore, the authors suggest that careful selection of evaluators be made to assess isometric torque of male water polo players (stronger evaluators when available).

Strength is a characteristic that can change over time, and the ability to measure this more often can have benefits for tracking changes in a sports population.[14] [The minimal detectable change identified in this study is large, and future work should investigate whether this measurement error is problematic to observe the changes expected over time.] Although hand-held dynamometers offer a superior clinical usefulness via cheaper costs and less specialized resources, they fail to provide an ongoing measure in the natural sports environment. Wearable technologies such as inertial measurement units or force gauges have the potential to provide this type of analysis in real-time and on an ongoing basis.[15] Further developments remain to decrease the error estimates of these technologies for monitoring purposes.

4.6.1 Limitations

A multi-evaluator design would have further allowed for inter-rater analysis, but the main objective was to compare the validity of hand-held dynamometers to isokinetic devices in a water polo population. This implies that the findings from this study may only be reproducible for experienced evaluators as well. Conclusions of this study cannot necessarily be generalised to other overhead sports or the general population. Finally, a methodology of multiple speed assessments and both concentric and eccentric measures on the isokinetic device would have yielded further information. One participant with a history of shoulder labrum repair did not feel comfortable with the isokinetic testing and was excluded from the analysis

4.7 Conclusions

Hand-held dynamometers are a valid, accessible clinical method to assess shoulder ER and IR strength in an elite water polo population. There was strong agreement between the two devices for absolute strength. There is less agreement at higher strength values. Therefore, we would recommend to maintain the use of a single device for longitudinal follow-ups in a group of players.

4.8 Acknowledgements

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Chapter 5. Risk factors for shoulder injuries in water polo: A cohort study

Félix Croteau, David Paradelo, David J Pearsall, Shawn M Robbins

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5.1 Preface

Chapter 2 identified multiple potential risk factors for shoulder injuries in water polo players, namely: range of motion, strength, scapular dyskinesis, throwing technique and workload. Preliminary investigations have shown a potential correlation between lack of strength and range of motion in water polo players. The study in Chapter 5 adds to this literature, whilst further evaluating the confounding effect of previous injury and scapular upward rotation with strength and flexibility on new injuries incidence.

5.2 Abstract

Background: Very limited investigations have been conducted exploring risk factors for injury in water polo players. A gap remains in the literature regarding identification of variables that should be considered as part of player screening evaluations.

Purpose: To estimate whether previous injury, changes in strength, range of motion (ROM) or upward scapular rotation (UR) are related to shoulder injuries in water polo players.

Study Design: Descriptive cohort study

Methods: Thirty-nine international-level players participated (19 males). Shoulder internal (IR) and external rotation (ER) peak torque was measured using an isokinetic device (CONtrex MJ). Shoulder ROM was measured passively using standard goniometry. Scapular UR was measured using a laser digital inclinometer. At baseline players were divided into groups: those with and without previous shoulder injuries. Independent t-tests and Mann-Whitney U tests were used to compare the study variables between groups. After nine months, a second analysis compared the same athletes, who were then grouped by those who had or had not sustained new injuries. Effect sizes were calculated with a Hedge's g. Chi squared analysis compared proportion of injured players with and without previous injury.

Results: Eighteen participants (46%) had previous injuries at baseline. Players with a previous injury showed higher peak torques for IR (0.62±0.15 vs 0.54±0.13N/kg, p=0.04, g=0.60); larger loss of IR ROM (9.9±9.1 vs 4.1±7.5°, p=0.04, g=0.68), but no statistical difference in UR (p=0.70). After nine months, there were no statistical strength differences between groups. Loss of IR ROM was significantly higher in the injured group (9.8±9.8 vs 4.0±6.7°, p=0.04, g=0.68), as well as UR (13.0±3.0 vs 10.4±3.3°, p=0.01, g=0.81). History of previous injury was significantly related to developing a new injury (OR 6.5, p=0.02). Logistic regression found previous injury and UR most important contributors to injury risk.

Conclusions: Previous injury, changes in IR ROM and UR are related to new shoulder injuries in water polo, but further variables such as rest, training load, or psychosocial factors may explain the incidence of new injuries.

Level of Evidence: Level 3

KEY WORDS: aquatic, athlete, dynamometer, injury prevention, shoulder

5.3 Introduction

Water polo is a popular aquatic contact sport, and has the highest rates of injuries amongst other aquatic disciplines during competitions (16.2% to 19.4%).[1] Although the majority of observed traumatic injury incidence occur to the head and fingers during matches,[2] the most common overuse injury area is the shoulder.[3-5] In order to decrease shoulder injuries in water polo, a better understanding of their risk factors is necessary to target prevention measures.[6]

Lack of strength may be related to a higher risk of injury in this sport,[3] as well as deficits in external rotation (ER) strength relative to internal rotation (IR) strength.[7] Previous authors have shown that water polo players are stronger than healthy non-players in abduction, adduction, ER and IR ($p<0.05$)[8,9] and showed lower ratios of ER over IR rotation strength.[9,10] Recently, Hams et al[11] have shown that sub-elite players (national development group) who were weaker in isometric ER and IR at baseline testing were more likely to have new shoulder injuries occur over the following three seasons. Furthermore, no significant difference was found between injured and non-injured groups for ER to IR strength (ER:IR) ratios. However, as Ham et al. performed isometric tests, testing shoulder strength with isokinetic devices at higher speeds may replicate the muscle activity which occurs during the throwing action and may yield different findings.[12]

Lack of shoulder range of motion has been shown to correlate strongly with shoulder injuries in swimming and overhead throwing sports.[13-16] Water polo players show greater ER, decreased IR, and increased total range of motion in their dominant shoulders compared to their contralateral side.[8,17] However, Elliott[18] found no statistical correlations between shoulder pain and ROM in a group of 13 male national team water polo players. In contrast, Hams et al[11] found that players in the injured group showed significantly less total range of motion (ER plus IR) ($p<0.05$). Thus, more evidence is needed to correlate injuries with ROM measures of the shoulder in water polo players.

Altered scapular posture is related to shoulder pain in throwing sports,[16,19] and it is hypothesized that the "head up" swimming pattern typical during water polo can also lead to impingement syndromes.[3] One group of authors found no differences between water polo players and healthy controls in scapular upward rotation (UR) using electromagnetic 3D kinematic measurements (frontal plane angle of the spine of the scapula vs a horizontal line).[20] Two-dimensional measurements of UR have also shown good to excellent reliability,[21] and have been implemented by other authors to assess water polo players. Mukhtyar et al[22] compared the scapular abduction position of healthy water polo players (n=16) to players with impingement symptoms (n=14) by measuring the distance between scapular angles and the spine after training. The group with shoulder impingement showed significantly decreased values for scapular abduction and UR ($p<0.05$) at 45° or more of shoulder abduction.[22] However, Witwer et al[8] did not observe these patterns of decreased upward rotation in a cohort of 31 collegiate water polo players (12 males and 19 females) in a rested state.

Previous researchers have investigated strength, ROM,[11,17] scapular alignment,[22] throwing variables,[23,24] and shooting volume[25] as potential risk factors for shoulder injuries. However, only one investigation was performed prospectively on sub-elite players, and none in other age groups. Therefore, the causal relationship between injuries and these variables remains unclear. Strength and ROM were the only variables measured in relation to shoulder injury incidence. Additional understanding of risk factors is necessary to inform effective injury prevention strategies in this sport. Therefore, the purpose of this study was to estimate whether previous injury, changes in strength, ROM or UR are related to shoulder injuries in water polo players. A secondary objective was to compare sex differences among these risk factors. Given previous findings, it was expected that weaker players with less ROM and less upward rotation of the scapulae would be at higher risk of injuries.

5.4 Methods

5.4.1 Subjects

Nineteen male and twenty female water polo players from the Canadian senior national team were selected for this cohort study. Participants had to have a minimum of five years of experience, and be training full-time in a high-level competition environment (at least five practices per week). Subjects with a history of shoulder injury or surgery were included if they were able to participate fully in all team training sessions at the beginning of the study. A formal sample size calculation was not performed because all members of the senior national teams in Canada were recruited (n=39). Further recruitment would have required the addition of lower level players that did not represent the target population. Data were collected at the training center at the Institut National du Sport du Québec in Montreal, Canada. This study received ethics approval from McGill University Ethics Institutional Review Board, in compliance with the Helsinki Declaration. All participants signed informed consent to take part in the study.

5.4.2 Procedures

Demographic data were collected for age, body mass index (BMI), hand dominance, player position and training setting. Shoulder passive ROM was assessed in ER and IR using a standard goniometer. Shoulder strength was assessed with an isokinetic device for ER and IR. Scapular UR was assessed with a digital inclinometer.

5.4.3 Range of Motion

Participants were positioned in supine, with the shoulder in 90° of abduction (Figure 5.1). A small lift was placed under the elbow to align the humerus parallel to the ground. The fulcrum [of the goniometer] was placed distally to the patient on the elbow, with the reference arm perpendicular to the arm and the measurement arm aligned with the styloid process of the ulna. The participant's shoulder was then brought passively into the maximal tolerated ER, and a measure was taken at the end position. The shoulder was then brought back to the resting neutral position, and the procedure was repeated to take a second measurement. The evaluator then changed sides to measure the contralateral shoulder using the same procedure. Next, the evaluator returned to the starting side and measured shoulder IR twice using the same procedure, which was finally repeated on the contralateral shoulder.

Shoulder ER ROM was obtained by taking the average of the two measurements. This was repeated for IR. Shoulder total range of motion was calculated at the sum of both ER and IR for each shoulder. Internal rotation loss was defined as the difference between shoulder IR from the dominant side compared to the non-dominant side.[26] External rotation gain was defined as the difference between shoulder ER of the dominant side with the non-dominant side.[26] Similar methods for measuring shoulder ROM have demonstrated very good inter-rater (intra-class correlations of 0.97 (ICC); 95%CI=0.89 to 0.99) and intra-rater reliability (ICC=0.95; 95%CI=0.87 to 0.98).[27]

5.4.4 Strength

Shoulder IR and ER strength was measured using a CON-TREX® isokinetic dynamometer (CON-TREX MJ; CMV AG, Dübendorf, Switzerland) with a protocol of

90°/s concentric/concentric contractions with a maximum torque tolerance of 250Nm sampled at 4000Hz. Participants were measured in supine with the shoulder placed in 90° of abduction to replicate the throwing position (Figure 5.2). All measurements were taken in the afternoon before practice to avoid testing in a fatigued state. Eccentric contractions were not employed to avoid muscle soreness prior to training. Participants were provided with an opportunity to perform 10 sub-maximal repetitions of IR and ER of the non-dominant side as a warm up. After a one minute break, participants were asked to “push against the machine as hard as [they] can” for five repetitions. Verbal encouragement was provided throughout the testing procedure. After a two minute break, the procedure was repeated on the dominant side.

Shoulder torque values provided by the CON-TREX® software were gravity-corrected. A custom RStudio[28] script was written to filter only the values measured at the target test speed of 90°± 0.5°/s. The peak value was identified as the maximum value recorded within this filtered subset and used for the rest of the analysis in the study. Measures of relative torque were calculated by dividing the absolute values by the participants’ body weight. Ratios were obtained by dividing the peak ER torques by the peak IR torques. Between-days repeatability of isokinetic dynamometers is very good to excellent for shoulder assessments (ICC = 0.85 to 0.97).[29]

5.4.5 Scapular Alignment

Scapular UR was measured using a Halo™ digital inclinometer (model HG1, HALO Medical Devices, Australia) after performing the dynamometer testing and with the participant standing with their shoulder in a 90° of abduction position (Figure 5.3). Scapular orientation was measured in the frontal plane only, and measurement of upward rotation was estimated by placing the fulcrum on the superior angle of the scapula and estimating the angle between the tip of the acromion and the horizontal plane. The participants were given 30 seconds to bring their arms down to rest, and the measure was repeated after the participants performed another 90° abduction movement. This was then repeated for the contralateral shoulder. Scapular UR was calculated by taking the average of the two measurements. This method was described previously to be reliable (ICC 0.81 to 0.94),[30] and the position of shoulder abduction at 90° was preferred to identify differences.[22]

5.4.6 Injury Surveillance

Injuries were defined in accordance with established consensus statements as any musculoskeletal injury or concussion for which the athletes required a consultation with a health care practitioner.[31] In order to establish previous injury counts at baseline, a database of medical records was reviewed with a focus on shoulder injuries that had occurred in the prior 12 months. This database is linked with the participants' electronic medical record (EMR), where every consultation with a sports medicine doctor, physiotherapist, or other health care practitioner had been entered and labelled for the corresponding injury accordingly. The EMR is maintained on a secure server with password encryption according to standards established by the *Collège des Médecins du Québec*. For the new injury incidence, an online surveillance program Hexfit™ (Hexfit Solutions Inc, Canada) was used to collect daily information on training loads and overuse injuries longitudinally for nine months of normal training and competitions. The system automatically flagged athletes who reported pain during training, and they were then contacted by the lead researcher to confirm that the injury qualified as per the study inclusion criteria. This method has been shown to be reliable in the past with a population of water polo players.[32]

5.4.7 Analysis

Given the small sample available for this study, groups were dichotomized at baseline by those who had sustained a previous shoulder injury and those who had not. An additional analysis was done after nine months follow-up to compare players with new injuries vs no new injuries. Most variables showed close to normal distributions, except for strength variables. Therefore, independent t-tests were applied to compare dominant shoulder ROM and UR variables between healthy and injured players. Range of motion comparisons were made for range into ER and IR, total range of motion, ER gain and IR loss compared to the non-throwing shoulder. Mean UR was compared for scapular alignment differences. Mann-Whitney U tests compared relative dominant shoulder strength and strength ratios between the healthy and injured groups. The variables compared were average relative peak torque in ER and IR as well as ER:IR ratios. Effect sizes were calculated to compare group means with a Hedges *g* correction approach given the sample size, with small effect described as values <0.2, medium effect <0.5 and large effects >0.8.[33] Male and female players were compared as groups using the same approach. A chi-square analysis compared the proportions of players with a new injury vs a previous injury.

A logistic regression was performed to estimate the relative impact of the risk factors on new injuries in an exploratory analysis. The dependent variable was the development of a new injury over the nine month follow-up (1=injury, 0= no injury). In the first step, a history of previous injury was entered as a confounding variable

(1=previous injury, 0=no previous injury). Next, a strength, ROM or UR variable were entered to determine if they related to the development of injuries over the nine month follow-up. Separate models were created for each strength, ROM or UR variable. The optimal model was decided as that which included only significant coefficients, provided the highest pseudo-R^2 value, and minimized the residual deviance. Odds ratios with 95% confidence intervals (CI) were also calculated for the variables included in the model based on the logit of the coefficients.

Figure 5.1 Participant setup for shoulder IR ROM measurement

Figure 5.2 Participant setup for shoulder ER and IR strength measurements

Figure 5.3 Participant setup for scapular UR measurements

5.5 Results

Nearly half of the participants in the study (18/39) had sustained a previous shoulder injury at baseline. Demographic variables were similar for the previously injured vs previously healthy groups in terms of age, sex, BMI, hand dominance, and training setting (Table 5.1). However, there were no goalies with previous shoulder injuries.

Table 5.1 Baseline demographic data

Variable		Previous Injury (n=18)	No Previous Injury (n=21)	New injury (n=19)*	No new injury (n=20)
Mean Age, years (SD)		23.4 (4.3)	22.8 (2.9)	22.5 (4.1)	22.7 (3.0)
Male (%)		10 (56%)	9 (43%)	9 (47%)	10 (50%)
Mean BMI (SD)		25.2 (3.2)	24.7 (2.2)	25.0 (3.2)	24.9 (2.2)
Hand dominance (n)	Right	17	20	18	19
	Left	1	1	1	1
Player position (n)	Goalie	0	7	2	5
	Set	9	6	9	6
	Driver	9	8	8	9
Training setting (n)	National center	5	8	6	7
	Professional	9	7	9	7
	College	4	6	4	6

*The groups were classified after the nine month follow-up into those who developed prospective injuries and those that remained healthy

Observations comparing dominant to non-dominant sides showed increased dominant shoulder ER ROM (105±11° vs 98±11°, p=0.01) and decreased IR (53±11° vs 59±10°, p<0.01). There was however no difference in total range of motion (p=0.98). However, there were no significant differences in strength (p=0.58-0.70) or UR (p=0.99). Findings for group comparisons of strength, ROM and UR can be found in Table 5.2 and Table 5.3.

The previously injured group showed no significant differences in shoulder ROM into ER, IR or in total range of motion. However, athletes with a previous injury showed greater IR loss on the dominant shoulder (moderate ES g=0.68, 95%CI=0.03 to 1.34) and higher mean relative IR strength (moderate effect size (ES), *g*=0.60; 95%CI=-0.05 to 1.25). The ER:IR ratios were not significantly different between groups (Table 5.2). No significant difference was observed in UR.

Table 5.2 Mean physical factors of the dominant shoulder for athletes with previous injuries and results of statistical comparisons.

Variable		Previous injury (n=18)	No previous injury (n=21)	Significance (p-value)	Effect size *g* [95% CI]
Strength*	ER (Nm/kg)	0.43 (0.10)	0.38 (0.11)	0.12	0.45 [-0.20, 1.09]
	IR (Nm/kg)	0.62 (0.15)	0.54 (0.13)	0.04	0.60 [-0.05, 1.25]
	ER/IR ratio	0.70 (0.10)	0.72 (0.11)	0.60	-0.16 [-0.79, 0.48]
ROM	ER (°)	105.1 (11.0)	104.8 (11.6)	0.93	0.03 [-0.61, 0.67]
	IR (°)	52.0 (10.2)	52.9 (11.7)	0.80	-0.08 [-0.72, 0.56]
	Total rotation (°)	157.1 (12.5)	157.7 (14.7)	0.90	-0.04 [-0.68, 0.60]
	ER gain (°)	7.7 (8.3)	5.1 (8.6)	0.35	0.30 [-0.34, 0.94]
	IR loss (°)	9.9 (9.1)	4.1 (7.5)	0.04	0.68 [0.03, 1.34]
Scapular UR	UR (°)	11.4 (3.0)	11.8 (3.7)	0.70	-0.12 [-0.76, 0.52]

*Strength variables were not normally distributed and groups were compared with Mann-Whitney test. ER = external rotation, IR = internal rotation, ER:IR = ratio of external over internal rotation, ROM = range of motion, UR = upward rotation.

Table 5.3 Mean physical factors of the dominant shoulder for athletes with new injuries and results of statistical comparisons**

Variable		New injury (n=19)	No new injury (n=20)	Significance (p-value)	Effect size *g* [95% CI]
Strength*	ER (Nm/kg)	0.40 (0.11)	0.41 (0.10)	0.92	-0.14 [-0.77, 0.50]
	IR (Nm/kg)	0.59 (0.14)	0.56 (0.15)	0.52	0.18 [-0.46, 0.81]
	ER/IR ratio	0.68 (0.12)	0.74 (0.08)	0.09	-0.61 [-1.26, 0.04]
ROM	ER (°)	104.9 (10.9)	105.1 (11.7)	0.96	-0.02 [-0.65, 0.62]
	IR (°)	49.9 (10.1)	54.9 (11.4)	0.16	-0.45 [-1.09, 0.19]
	Total rotation (°)	154.8 (12.6)	160.0 (14.3)	0.24	-0.37 [-1.01, 0.27]
	ER gain (°)	7.7 (8.4)	5.0 (8.5)	0.33	0.31 [-0.33, 0.95]
	IR loss (°)	9.8 (9.8)	4.0 (6.7)	0.04*	0.68 [0.03, 1.33]
Scapular UR	UR (°)	13.0 (3.0)	10.4 (3.3)	0.01*	0.81 [0.15, 1.47]

*Strength variables were not normally distributed and groups were compared with Mann-Whitney test. ** Three male athletes quit water polo during the study follow-up period, and were included in the prospective injured group because they had prior injuries. ER = external rotation, IR = internal rotation, ER:IR = ratio of external over internal rotation, ROM = range of motion, UR = upward rotation.

At the nine month follow-up, players were once again divided into two groups based on the presence of a new shoulder injury (Table 5.3). Three players from the men's team quit the program during the study, but had already developed new shoulder injuries before they left. Therefore, they were classified into the group with new injuries (n=19). A chi-square test confirmed that the players that had a previous injury were significantly more likely to develop new injuries (71.4% vs 27.8%, p=0.02). Furthermore, dominant shoulder

IR loss was significantly higher in the group with new injuries ($p=0.04$, ES=0.68). Relative strength values were not different between groups, but UR was significantly greater in the group with new injuries ($p<0.01$, ES=0.81).

Sex comparisons showed that female players demonstrated higher total range of motion in rotation ($p=0.02$, ES $g=0.75$). Males were much stronger than the female players in both ER and IR, respectively ($p<0.01$, large ES $g=2.03$, 2.04), but ER:IR ratios were not different (Supplemental Table A5.5). No other variables were significantly different between sexes.

The best model fit to explain new injuries included previous injuries and UR (Table 5.4). This model minimized residual deviance (37.04) and maximized the pseudo-R^2 value using the Nagelkerke method ($R^2=0.47$). The odds ratios (OR) for history of previous injury are 6.5, (95%CI=1.6 to 26.4), and increased UR was related to more likelihood of developing a new injury (OR=1.5, 95%CI=1.1 to 2.0) after accounting for a previous injury. No other variables were significantly related to new injuries in the logistic regression analyses.

Table 5.4 Significance of risk factors in a logistic regression with previous injury as a confounder

Variable	**Coefficient**	**p-value**	**R^2 (Nagelkerke)**
Sex=male	-0.42	0.57	0.25
Relative external rotation strength	-4.54	0.23	0.28
Relative internal rotation strength	-0.72	0.78	0.24
Ratio external/internal rotation strength	-7.07	0.08	0.34
External rotation flexibility	-0.01	0.92	0.24
Internal rotation flexibility	-0.05	0.15	0.30
Total rotation flexibility	-0.03	0.22	0.28
External rotation gain	0.03	0.51	0.25
Internal rotation loss	0.07	0.17	0.29
Scapular upward rotation	0.39	0.01	0.47

Previous injury was entered as the first confounder, and then a separate model was created with each variable above.

5.6 Discussion

Overall, this study showed that shoulder ER and IR ROM, strength, and UR are risk factors associated with shoulder injuries in water polo. At baseline, players with previous injuries demonstrated statistically significantly [higher] IR strength and loss of IR ROM on the dominant side. After nine months (and redistribution into injured/uninjured groups) strength measurements were not significantly different, but rather IR loss (greater in injured athletes) and UR showed a positive association. Largely, the most important predictor of new injury was the presence of a previous injury, with a 6.5 times increased odds of developing a new injury with this risk factor. Finally, male players showed higher strength values and less total ROM than their female counterparts.

Measures of relative IR strength were the only strength variable correlated with previous injury, and no strength variables were associated with new injury. In their group, Hams et al[11] found that high-level Australian water polo players with lower isometric strength had an association with new injuries. In the present study, relative IR strength was significantly higher for the group with previous injuries, but was not related to new injuries. The higher values of dominant shoulder strength for athletes with previous injuries may reflect that they may have been more likely to be performing targeted strengthening exercises to avoid new injuries, and thus demonstrated stronger test values. Consistent with Hams et al,[11] ER:IR strength ratios were not associated with new injuries, which suggests that asymmetries in rotator cuff strength may not be as widely present as was once suspected in this population.[3]

A greater loss of IR ROM was significant in the injured groups at baseline and after nine months. All other measures of ROM were otherwise similar between healthy and injured groups, and consistent with previous authors.[8,18] [The ability to create deceleration would be directly related to muscle's eccentric power. A limited ROM would require the deceleration to occur over a shorter period of time (the same energy would need to be absorbed and dissipated by the muscles over a shorter period of time), thus requiring more power (and higher muscle stress). Some of that stress could also be absorbed by other joint structures]. Over time, this can lead to pathologies such as those observed in this population with MRI which affect the postero-superior area of the gleno-humeral joint.[34-36] A loss of shoulder IR ROM may also decrease the mechanical efficiency of the pulling motion of swimming, where players would need to increase scapular tilting to bring the arm in an optimal mechanical position. This in turn can lead to an increase in mechanical stress on the anterior structures of the shoulder such as the acromio-clavicular joint and [its muscles].[37]

The injured group at follow-up showed a significantly higher dominant shoulder mean UR. This variable was also a key factor in the logistic regression model, showing that increasing UR contributes to the risk of sustaining an injury. Based on previous studies, it would rather have been expected to find decreased values in the injured group.[38] These findings may be the result of limiting measurement to static positions where the range of values observed was narrow. Active movement measured with three-dimensional kinematic equipment would be more precise. Furthermore, Mukhtyar et al[22] found significant differences between injured and non-injured water polo players only when the players were in a fatigued state after training. The task of repeated shoulder rotations on the isokinetic dynamometer may not have stressed the scapulo-thoracic musculature sufficiently, and may not have induced the type of fatigue expected after water polo training.

The male players showed significantly higher relative strength compared to the female players in both ER and IR. This can be the result of different training methods, or a reflection of the more physical demands of the sport in the men’s style of play. Given that female players use a smaller and lighter ball, this may decrease the impact of lower strength on their ability to generate powerful overhead throws, but comparisons between sexes are lacking in the literature. The increased ROM that the female players demonstrated may be advantageous to accelerate the ball over a larger distance before throwing. However, this increased ROM may be an added risk factor for specific types of shoulder pathologies affecting joint stability.[39]

The study is limited in its generalizability given the small sample size. However, this sample included the entire population of international level water polo players in Canada, and the findings remain important for this group. A twelve-month follow-up was planned, but confinement due to COVID-19 pandemic interrupted all training activities after nine months. Secondly, a test of eccentric ER strength using the isokinetic dynamometer would allow to calculate a functional ratio of strength at the shoulder that resembles the throwing motion more closely (concentric IR to eccentric ER). In this study, this method was not chosen in order to limit fatigue before training sessions. [Other methods could also mimic throwing more closely, i.e. using a cable resistance with a linear encoder.] Further studies investigating strength should consider this approach. Third, the methodology for measuring UR was optimal in the training setting, but it cannot yield information about active range of motion. In addition to taking all the measurements after training, future research should include a more substantial fatigue protocol to explore the conclusions of Mukhtyar et al.[22] Finally, other important risk factors were not considered, such as training volume and psychological factors.[40]

5.7 Conclusion

In conclusion, the results of the current study indicate that a history of previous injury, as well as measures of shoulder IR and UR were most strongly associated with risk for sustaining a new injury in a sample of international level players of both sexes. This study adds to a small body of Level 2[41] literature on risk factors for shoulder injuries in water polo. These findings indicate that monitoring shoulder ROM, UR, and strength should be considered as core elements of an injury prevention program for water polo players. Additional studies which investigate the effectiveness of different protocols to optimize strength ratios and ROM are needed to guide these programs.

5.8 Chapter 5 references

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Chapter 6. Automatic detection of passing and shooting in water polo using machine learning

Félix Croteau, Francois Thénault, Stefanie Blain-Moraes, David J Pearsall, David Paradelo, Shawn M Robbins

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6.1 Preface

In the later section of Chapter 2, a thorough summary of workload and its measurement in team sports was presented. While Chapter 5 presented the results of a cohort study on risk factors in water polo, workload was not included as part of the variables investigated. This was excluded because of a lack of available tools to measure external load. In Chapter 6, a study is presented that aimed at developing the methods required to objectively quantify workload in terms of overhead throwing volume. This was performed using wrist and lower-back worn IMU sealed in a waterproof plastic. Analysis of the multiple outputs from the IMU were conducted using machine learning algorithms.

6.2 Abstract

Objective: To develop a method to detect passes and shots in water polo automatically using inertial measurement units (IMU) and machine-learning algorithms.

Design: Cross-sectional.

Methods: Eight water polo players (four male and four female) wore one IMU sensor on the wrist (dominant hand) and one on the sacrum during six practices each (Physilog5, GaitUp™, Switzerland). All sessions were filmed with a Canon VIXIA video camera at 30Hz and manually tagged for individual shots or passes. Data were synchronized between throws and IMU sensors using a cross-correlation approach. Support vector machine (SVM) and artificial neural networks (ANN) were compared based on sensitivity (proportion of true positives) and specificity (proportion of true negatives).

Results: A sum of 7294 actions were identified during the training sessions, including 945 shots and 5361 passes. Using SVM, passes and shots together were identified with 94.4%

(95%CI=91.8-96.4, $p<0.05$) sensitivity and 93.6% (95%CI=91.4-95.4, $p<0.05$) specificity. Using ANN yielded similar sensitivity (93.0% [95%CI=90.1-95.1], $p<0.05$) and specificity (93.4% [95%CI=91.1=95.2], $p<0.05$). Using information from the wrist sensor only changed the performance markers by less than 1%. Analysis of shots separately was classified with 68.2% (95%CI=58.4-77.3, $p<0.05$) sensitivity and 97.2% (95%CI=95.9-98.1, $p<0.05$) specificity. Passes separately were identified with 88.6% (95%CI=84.8-91.6, $p<0.05$) sensitivity and 91.2% (95%CI=88.8-93.2, $p<0.05$) specificity.

Conclusion: The IMU data allowed [successful identification] overhead throwing motions with enough precision for field applications. A setup with one single sensor is best suited to identify these events if placed on the dominant wrist, and had less than 1% change of precision on estimates.

Clinical implications: This method can serve to track training load in water polo players. Clinicians can monitor these metrics to optimize progressive adaptations and minimize injury risk in these athletes.

Key words: water polo, inertial measurement unit, machine learning, workload

6.3 Introduction

Water-polo is an Olympic team sport with a high rate of shoulder injuries.[1,2] Risk factors for the most common injuries of the shoulder area include mobility restrictions, loss of strength, poor scapular alignment, and large overhead throwing volumes.[3] The sport requires a large amount of high-speed swimming bouts, as well as large repetitions of shooting (as many as 400-800 throws per practice).[4] Wheeler et al (2013) previously concluded that 74% of self-reported shoulder soreness was attributable to this shooting volume ($R^2 = 0.743$, p=0.01), with shorter breaks between shots also being a significant contributing factor (p=0.03).[5] To date, this is the only observational study focusing on overhead throwing volume in relation to injury in water polo. Although the conclusions have important implications for strategies to reduce injury risk, this previous study counted throws manually, which is both labour-intensive and time-consuming.

For water polo players, training (external) workload metrics could include distances [swum] and the number of overhead shooting actions performed. External workload here refers to "the cumulative amount of [mechanical] stress placed on an individual from multiple training sessions and games over a period of time".[6] The workload-injury model suggests that a progressive cumulative volume of training is important to build more robustness in athletes, and improve performance. However, a sudden rise in workload can predispose the same athletes to injury. Hence, an intermediate zone exists in which training exposures should be planned progressively to maximize physical adaptations and minimize injury risk. The optimal cut-off points for this zone can vary greatly between studies [and between individuals], leading to some difficulties with the application of these concepts in a sports environment.[7,8] Investigations into other throwing sports such as handball,[9] baseball[10] and cricket[11] have attempted to identify these guidelines, but challenges remain in their implementation in training.[12,13]

Measuring workload in water polo poses further specific challenges: GPS systems cannot be used when players train in an indoor pool, and any choice of wearable technology must be fully water submersible. Given the rapid changes in direction, and the multiple types of actions that are inherent to the sport, the use of waterproof inertial measurement units (IMU) affords a faster and less labour-intensive solution than manually counting actions on film.[5] IMU are comprised of three-dimensional accelerometers and gyroscopes, and are a popular type of wearable sensor to capture external load in team sports, both on field and court settings.[14,15] Thresholds of acceleration or angular velocity can be set to identify specific events such as a step during a walking task.[16] Recent uses of machine learning algorithms have improved the accuracy of the estimates of event counts by searching for patterns among the kinematic outputs from the IMUs.[17] Challenges remain however in detecting events at higher speeds while maintaining a high degree of accuracy.[18]

With the addition of machine learning classifiers, the process of identifying actions can be automated, thus reducing considerably the resources required to collect this information.[19] There are many approaches to reach this goal, and the optimal selection of machine learning classifier is dependent on the type of data studied.[20] In team sports, former work that focused on handball players has successfully achieved an accuracy of 85-90% identification of the two throw types in their sport using random forest algorithms.[9] Whiteside et al (2017) reached a mean accuracy of shot classification in tennis of 93.2% for nine subtypes using six different types of algorithms.[21] Recent studies suggest that deep learning (neural networks with many more layers) may provide superior accuracy to identify sport-specific movements, but they also require much larger datasets to train.[22]

Given that workload (i.e. throwing volume) is an important risk factor for shoulder soreness in water polo, it is important to measure this variable accurately and at minimal cost. No previous research has attempted to quantify water polo throwing workload using wearable sensors and machine learning. Thus, the main objective of this study was to develop a method to identify the quantity and type of throws in water polo using IMU and machine-learning classifiers. A secondary analysis aimed to compare two different machine learning approaches, and to identify differences in accuracy between using single versus two sensor setups. Our hypothesis is that a single-sensor system worn at the wrist should yield an accuracy above 90% to predict overhead throwing tasks with either support vector machine or artificial neural networks.

6.4 Methods

6.4.1 Participants

Four male (mean age 21±1years, BMI 24.8±0.8kg/m^2) and four female (mean age 26±2years, BMI 23.0±2.2kg/m^2) water polo players from the senior Canadian national teams participated in this cross-sectional study (two left-hand dominant). All eight players trained in more than five weekly water polo sessions, were ≥18 years old, and competed at the international level. Participants were excluded if they had a history of shoulder pathology or ongoing pain. All sessions were recorded over one week at the training facilities of the national team at the Institut National du Sport du Québec, Canada. This study received ethics approval from McGill University Ethics Institutional Review Board, in compliance with the Helsinki Declaration (study 01-M01-20A). All participants signed informed consent to take part in the study.

Previous research has shown that a minimum of 500 repetitions of each movement class is needed to develop a robust and generalizable algorithm.[23] A pilot data collection yielded an average of 148±65 events per athlete for each practice (individual sessions). These were further categorized into seven event subclasses (7x500 needed). Therefore, a target of sample 34 individual sessions or more was sought to generate a conservative sample greater than 5000 events. Six practices for each participant were recorded to allow for potential loss of data or uneven occurrences of event subclasses. A homogeneous sample would be less robust at identifying throwing motions in a novel data set, therefore both male and female players were included.

6.4.2 Data collection

Each participant was fitted with two Physilog 5 IMU’s (GaitUp™, Switzerland; accelerometer range ±16g, gyroscope range ±2000°/sec, sample rate 128Hz) that had been previously vacuum-sealed into a plastic envelope for waterproofing, and secured to the player with tape. The first sensor was placed on the dorsal aspect of the dominant wrist, with the X-axis aligned along the long axis of the forearm towards the hand (see Figure 6.1a). The second sensor was placed on the sacrum with the X-axis aligned parallel to the spine towards the cranial direction (see Figure 6.1b). Sampling rates were set to 128Hz to avoid aliasing of the data when evaluating high-speed throwing motions.[24] Simultaneously, two Canon VIXIA HFG20 video cameras (30Hz) filmed the training sessions with a bird’s eye view from perpendicular perspectives to limit blind spots in the sequence (see Figure 6.2). The video footage provides the gold standard as labelled by an evaluator and was used to compare with the IMU data. Once the participants were ready, they performed a standard posture of arms raised at 90 degrees of abduction for 5 seconds, then overhead in full abduction for 5 seconds, and finally tapped their sensors three times before entering the water to signal the beginning of practice. This was necessary to synchronize the IMU data with the video footage. Previously, this method was shown to be successful to identify the starting point of tennis training sessions.[21] Normal practices were recorded, with a typical format where the players swam for the first 20 minutes of training, then practiced passing with teammates. Next, athletes practiced shooting on the net in a non-contact situation, and practices ended with game-like scenarios.

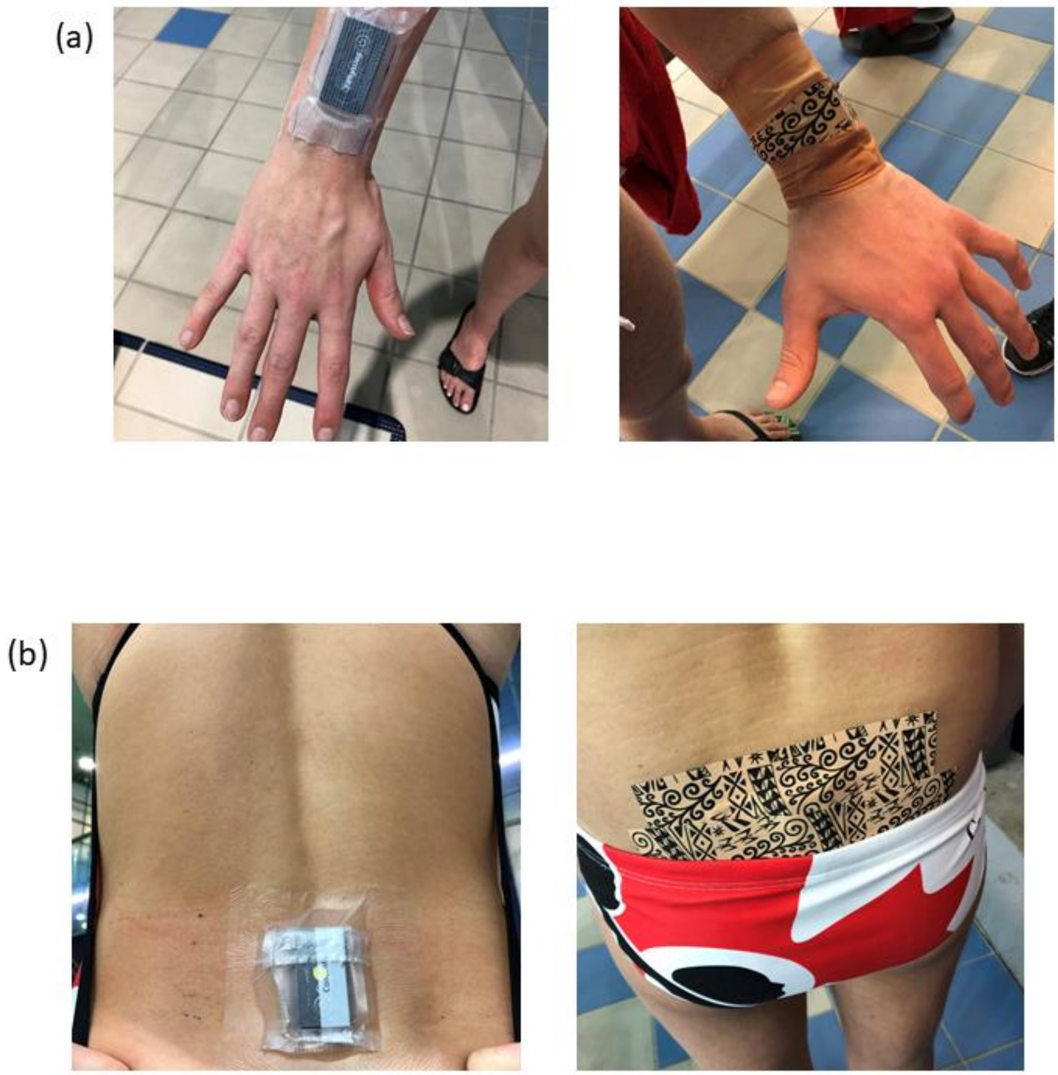

Figure 6.1 IMU sensor attachment to (a) the wrist and (b) the lower back

Figure 6.2 Camera setup for external validation

6.4.3 Labelling the dataset- Video data

Next, evaluators labelled the video footage to identify the onset and type of “true events” occurring in the pool, specifically passing and shooting. After an initial meeting to observe and understand footage examples of each subclass of passing and shooting, three evaluators independently labelled a sample video clip to verify agreement in event classification and onset identification. Shots and passes (main two classes) were identified based on the moment where the ball left the hand of the player. There were no discrepancies in labelling of the sample clip. The entire video footage was then labelled to identify two subclasses of passes: (1) regular passes and (2) wrist passes. Four subclasses of shots were also labelled as: (3) overhead shots, (4) lobed shots, (5) sweep shots, (6) back-hand shots (see Table 6.1 for definitions). Finally, (7) defensive blocks were also identified separately, but not otherwise used in the analysis. The inclusion of subclasses and blocks was intended to identify potential causes for discrepancies between the predicted and the observed classes later on. Pilot data showed that faking actions prior to shooting reduced the precision of predictions from the IMU data, and so these were identified on the video footage. Faking time stamps were set as the moment where the ball reached its most forward position during the faking action. This served to confirm if an inaccurate prediction was caused by a faking action.

Table 6.1 Definitions of subclass categories

Subclass name	**Definition**
Regular pass	Overhead throwing to a teammate
Wrist pass	Throwing to a teammate without significant shoulder motion
Overhead shot	Overhead throwing aimed at the net with high intensity
Lob shot	Overhead throwing with a high arc movement and lower intensity
Sweep shot	Overhead throwing where the throwing arm was brought rapidly across the body into adduction, releasing the ball at a low height from the water
Backhand shot	Participants threw the ball at the net behind their back in a horizontal abduction movement
Defensive block	Defined as the moments where the ball made contact with the participant's hand

Synchronization between the IMU data and the video time stamps using the three rapid taps method proved insufficiently precise with our data.[25] In its place, a cross-correlation technique was used to match data peaks with the tagging files.[26] This technique is a convolution between the normalized norm of the wrist acceleration and an event vector (1 for event, else 0) which produces a similarity vector. Visual inspection of the resulting graphs confirms the alignment and frames were either removed from the beginning or the end of the tagging files as necessary to reach optimal calibration. The wrist and lower back sensors were then cross-correlated to each other as well.

6.4.4 Data processing- IMU data

The raw data from the IMU's accelerometer and gyroscope in all three dimensions was exported into MATLAB (MathWorks, Natick, MA, USA) to filter and organize the data. First, a band-pass (4-20Hz), 4^{th} order Butterworth filter was applied to remove noise from the data according to previous findings from pilot measurements. Next, a window of 1 second was established on the IMU data to cover the complete actions of throwing or passing from onset to follow-through. The window was aligned on the exact moment of ball release as identified by the video footage, with 60% before and 40% after that moment. A longer window would potentially underestimate the number of actions occurring rapidly,[27] and a shorter window may be too small to identify a full throwing motion with faking. Control windows were identified 1 second before or after the tagged actions in the video footage. Other control windows were randomly selected throughout the IMU data as well to have enough examples for the machine learning classifiers. These control windows help identify motions of the arm that are none of the seven subclasses identified above. Since water polo practices involve swimming and grappling tasks as well as throwing, these activities could have been falsely interpreted as throws otherwise.

Next, a series of features were targeted to evaluate different aspects of the IMU signal. These were input to the machine learning classifiers to distinguish between classes. The key features from the IMU data were selected based on previous methods[17] including mean magnitude of signal, 25^{th}-50^{th}-75^{th} percentile ranks, measures of kurtosis and skewness, maximum amplitude, root mean square, autoregressive 4^{th} order coefficients (four total), maximum frequency, and the sum of the frequency spectrum below 10Hz. This yields 14 features per sensor in six axes (three for the accelerometer and three for the gyroscope), for a total of 84 features to be extracted in each window. The wrist and lower back sensors together produce 168 features, and hence principal component analysis (PCA) with singular value decomposition (SVD)[15] was used to reduce the dimensionality of the analysis. This method decreased the number of variables that were highly correlated to each other, keeping only those which explained over 90% of the variance in the outcome.[28] The remaining features were hard normalized between 0 and 1, where 1 equals the maximum value for each of the selected components of the PCA. This allows for a weighed comparison of the features for the classifiers.

Next, the pre-processed dataset was divided into a training set and a test set using a “leave one subject out” approach (LOSO). Specifically, the machine learning classifiers were trained using seven of the eight participants’ data. This training dataset was used to generate an algorithm that separates the IMU data into each of the classes labelled on the video footage. The one participant left out of the training dataset was used in the test dataset. This test dataset was used to validate the correct predictions of the algorithm on new data. The process was repeated for all eight permutations of participants (i.e. test on subject 1, then test on subject 2, etc.) and the average accuracy and associated statistics were calculated as described in the analysis section below.

The shots class were up-sampled using a “Safe-Level-Synthetic Minority Over-Sampling Technique” (SMOTE) to balance shots and passes more evenly.[29] Failing to balance the classes would bias the algorithm towards higher recognition of the patterns presented more often in the dataset. Finally, the machine learning classifiers aim to identify movement classes using these processed data. Two different machine learning classifiers were included and compared to find the best one to identify throws accurately: support vector machine (SVM) and artificial neural networks (ANN). SVM acts in a similar way to linear regression by searching for the plane that separates the data into classes with the largest distance between classes.[30] In the current study, a sweeping method using Matlab's Bayesian optimization established gamma and internal parameters (C). ANN works by setting a predefined number of nodes, where data are filtered into categories based on a weighed probability (i.e. mean > 50%). The ANN then adjusts the weights of the categories by attempting to match the output of its classification with the labelled dataset via a process called backpropagation.[30] In the present study, the ANN was built with two layers of nodes, and an optimal nodes number was set by attempting to classify with 2 to 40 nodes, in increments of two.

6.4.5 Data Analysis

Model performance was evaluated by testing its correct identification of events in a separate test dataset. This evaluation was performed for each of the three sensor combinations (wrist only, back only, or using both sensors) as well as both separate or combined event classes (shots vs passes vs control, or shots AND passes vs control). A complete confusion matrix was developed for the two classifiers (SVM and ANN) to show the average observed vs average predicted classes. This table was used to calculate classical performance metrics of machine learning algorithms: accuracy, precision, recall/sensitivity, F1 score and specificity (see McGrath et al (2019) for definitions).[24] For neural network approaches, a receiver operating characteristics curve (ROC) was drawn to identify model performance based on the area under the curve (AUC). A bootstrapping technique was employed to generate 95% confidence intervals for each of the performance indicators of the predictions. Permutation tests were performed to evaluate the significance of the predicted outcomes vs random chance alone.

6.5 Results

Data were collected for eight participants over six practices each (48 individual sessions), but there were four individual instances where the sensors were not activated properly when installed (three male and one female participant). The final dataset yielded a total of 7294 events, with subclasses for 5361 regular passes and 509 wrist passes, 945 overhead shots, 77 lob shots, 91 sweep shots, 50 backhand shots and 261 fake shots. Most of the subclasses did not include enough events (>500) for inclusion into the final models, and thus only regular passes and overhead shots were included. The lower back sensors detached partially from the male participants in eight instances, and thus a subset of 37 individual sessions was used to run the full three class model (5932 events remaining, with subclasses for 716 overhead shots and 4358 regular passes). A visual representation of the processed wrist IMU data showed that the subclasses for overhead shots and sweep shots had the highest average values of accelerations and angular speeds but included values spreading over a very large range (Figure 6.3).

6.5.1 Main model evaluation of two classes with two sensors

Table 6.2 presents the confusion matrix of shots and passes vs control using SVM with both the wrist and back sensors. The SVM classifier gamma was a third order polynomial and C=0.0527. SVM predicted correct class with with 94.4% (95%CI=91.8-96.4, $p<0.05$) sensitivity and 93.6% (95%CI=91.4-95.4, $p<0.05$) specificity. Using ANN

(49 nodes first layer and 26 second layer) yielded similar performance with 93.0% (95%CI=90.1-95.1, p<0.05) sensitivity and 93.4% (95%CI=91.1-95.2, p<0.05) specificity.

6.5.2 Model with two classes and only one sensor

The classifiers were also trained using only the wrist IMU data or the only the back IMU data. The SVM approach (gamma = Gaussian, C=3.437) using one single sensor at the wrist compared to two sensors changed the sensitivity from 94.4% to 95.3% (95%CI 92.9-97.1, p<0.05) and specificity from 93.6% to 93.1% (95%CI 93.1-95.0, p<0.05). With the ANN classifier (23 nodes first layer and 22 second layer), predictions with just one sensor at the wrist yielded 94.2% (95%CI=91.5-96.2, p<0.05) sensitivity and 93.0% (95%CI=90.8-94.9, p<0.05) specificity. Using one single sensor at the lower back further reduced SVM sensitivity to 78.5% (95%CI 74.7-81.9, p<0.05) and specificity to 88.6% (95%CI 85.5-91.0, p<0.05) (gamma = second order polynomial, C=21.61).

6.5.3 Full model evaluation of three classes

The model was also trained with the intention to classify passes, shots and control windows separately (three classes). Using SVM (gamma = third order polynomial, C=0.302), shots were identified with 68.2% (95%CI=58.4-77.3, p<0.05) sensitivity and 97.2% (95%CI=95.9-98.1, p<0.05) specificity. Passes were identified with 88.6% (95%CI=84.8-91.6, p<0.05) sensitivity and 91.2% (95%CI=88.8-93.2, p<0.05) specificity. This SVM model took 150min to train and 490sec to test on new data (using LOSO). Using ANN (46 nodes first layer and 38 second layer), throws were identified with 58.8% (95%CI=48.8-68.9, p<0.05) sensitivity and 98.6% (95%CI=97.6-99.2, p<0.05) specificity. Passes were identified with 89.0% (95%CI=85.4-92.0, p<0.05) sensitivity and 91.2%

(95%CI=88.8-93.4, $p<0.05$) specificity. This model took 15min to train, and 70sec to test on new data (using LOSO).

Table 6.2 Confusion matrix showing mean results* for support vector machine (SVM) and artificial neural network (ANN) classifiers with two classes using two sensors (wrist and back)

		Observed			
		SVM		**ANN**	
		Shots and passes	**Control**	**Shots and passes**	**Control**
Predicted	Shots and passes	468	34	468	35
	Control	23	629	28	624

*The results are rounded to the nearest decimal, and as such there are small differences in total observations between the two classifiers.

Table 6.3 Performance measures for the support vector machine (SVM) and artificial neural networks (ANN) using two sensors (wrist and back).

	SVM			ANN		
	Two classes	Three classes		Two classes	Three classes	
	SP	S	P	SP	S	P
Accuracy (95%CI)	93.9% (92.3-95.3)	94.9% (93.3-96.1)	90.2% (88.2-91.9)	93.2% (91.5-94.7)	94.8% (93.3-96.1)	90.4% (88.4-92.2)
Precision (95%CI)	91.7% (88.8-94.0)	72.8% (60.8-82.8)	85.5% (81.7-88.8)	91.4% (88.5-93.8)	78.9% (65.6-88.3)	85.3% (81.6-88.8)
Recall/sensitivity (95%CI)	94.4% (91.8-96.4)	68.2% (58.4-77.3)	88.6% (84.8-91.6)	93.0% (90.1-95.1)	58.8% (48.8-68.9)	89.0% (85.4-92.0)
F1 score (95%CI)	93.0% (91.0-94.6)	68.7% (59.9-77.1)	86.9% (84.0-89.4)	92.1% (90.1-93.9)	65.3% (56.0-74.1)	87.0% (84.3-89.6)
Specificity (95%CI)	93.6% (91.4-95.4)	97.2% (95.9-98.1)	91.2% (88.8-93.2)	93.4% (91.1-95.2)	98.6% (97.6-99.2)	91.2% (88.8-93.4)
AUC	-		-	97.4% (96.3-98.2)	94.5% (88.8-97.3)	95.0% (93.4-96.3)

AUC = Area under the curve; S=shot, P = pass, SP = shot AND pass (two class model)

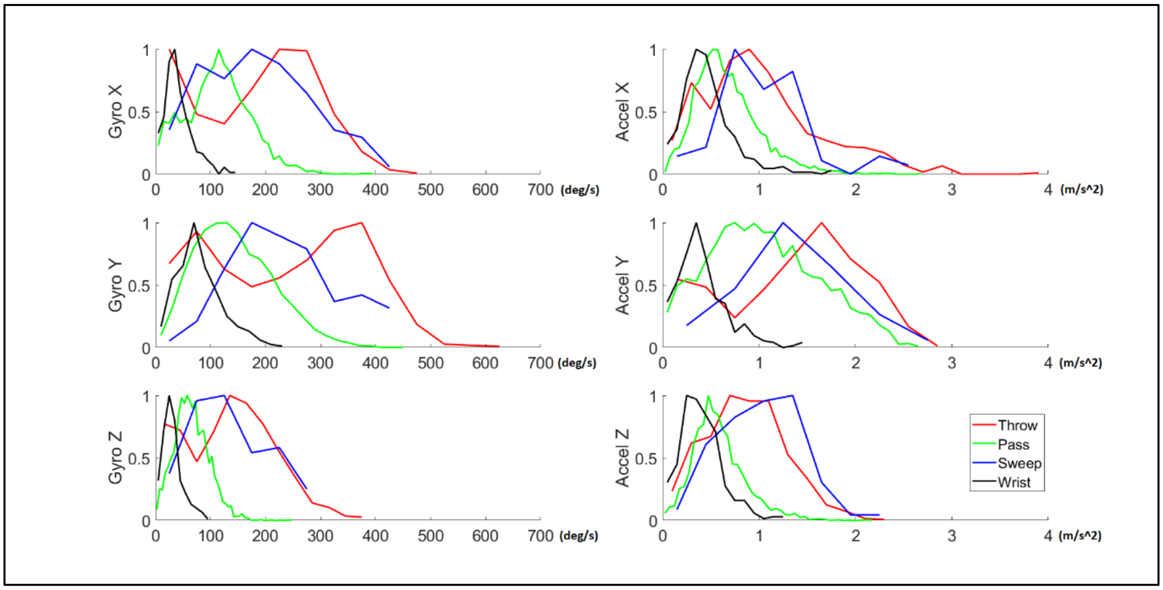

Figure 6.3 Distribution of the 90th percentile accelerations and angular speeds at the wrist IMU in three dimensions for all tagged categories.

6.6 Discussion

Our results showed that IMU sensors are well suited to measure throwing motions in water polo using machine learning. The performance parameters indicate that the two class model that includes passes and shots together is superior to classification separately with the current dataset. Furthermore, the SVM classifier outperformed the ANN by a marginal amount, suggesting that both approaches can handle this type of data adequately. Given that ANN is much faster to process (10 times faster to train and 7 times faster to test new data), this would be a more optimal approach to classify similar data. Accuracy from one single sensor at the wrist is not significantly different than using both sensors, and as such, this simpler setup is recommended to optimize athlete adherence.[31] This study exemplifies that workload can be successfully estimated using IMU and machine learning in terms of overhead throwing activities. Clinically, data recorded during training sessions and matches can be submitted directly to the resulting algorithms without the need for labelling any of the video footage.

The accuracy levels of 93.2-93.9% ($p<0.05$) from the two-class models using both sensors are comparable to those obtained in previous publications using similar methodology.[27] Recently, Jowitt et al (2020)[27] constructed a superior random forest algorithm of cricket fast bowling using more than 20,000 events from both training and competition situations, achieving a sensitivity of 96.3-99.6%. Using a larger dataset also lead to better predictions (up to 97.4% accuracy) in a study of >28,000 tennis events using six different classifiers (including SVM and ANN).[21] With a smaller sample of <1000 events, a study of handball players showed an accuracy of shot type prediction (circle or whip) of 85.4% with random forest classification.[9] Altogether, these findings show that increasing sample size of the observed events is key to optimize model predictions.

The use of a single sensor mounted at the wrist showed non-significant differences in precision compared with using both the wrist and back sensors (demonstrated by the confidence interval overlap). This was expected given the proximity of the sensor to the activities observed.[21] Although most comparable studies in overhead throwing sports have been performed with single sensor setups, Steels et al (2020) showed that placing the sensor on the badminton racquet was more precise than leaving it at the wrist (98% vs 93% accuracy).[22] However, water polo players also use their dominant arms while they are swimming, blocking and grappling with their opponents. Therefore, considerably more noise is expected as part of the IMU signals obtained. McNamara et al (2015)[32] indeed found that the accuracy of their predictions decreased from 98.1% to 74.0% when attempting to predict bowls in a dataset made from competition situations using their algorithm developed with practices only. In their discussion, they mention that an important source of noise in the data came from submaximal throws that were aimed at their teammates. This variety of speed and intensity for a similar task is closer to those recorded in the current study, which still yielded higher accuracy.

The variability in shooting and passing intensity is a source of noise in the raw data for this study as well. Figure 6.3 shows considerable overlap in the signals of regular passes and overhead shots in terms of accelerations. The confusion matrices for the three class model further show that the most common mistakes in prediction from the classifiers occurred between passes and shots as opposed to control windows (Appendix table A3). Fortunately, more distinction between the most frequently observed peak values was obtained in the gyroscope data. This is consistent with the findings from previous authors as well.[9,22] The inclusion of these artefacts decreased the performance of the classifiers, but the resulting predictions were more ecological than the activities performed in previous studies.[9,24,32] Furthermore, the two class model was still very accurate regardless of this noise.

6.6.1 Limitations

Although the sample of repetitions of overhead shots and regular passes was adequate, the total number of participants remained small in this study. This may yield a model that is over-fitted to our subjects, and less generalizable to others. Furthermore, the loss of data due to sensors detaching was greater in the male participants vs the females, leaving a total of 3992 events for the female participants vs 1939 for the males. Again, this may have over-fitted our model towards female players. Next, challenges occurred with regards to synchronizing the video and IMU data sources. The approach of standard postures with three taps of the IMUs did not match the two sources of data with sufficient precision, but high-speed cameras may yield superior results. Finally, our findings showed that the algorithms struggle to identify events clearly when the athletes perform multiple faking actions. The patterns for these actions can vary, where some strategies involved circular motions above the head, quick flexion/extension movements of the elbow, rapid and sudden changes of speed in the throwing motion, etc. This may result in a fluctuation of the intensity and the duration of the faking action, and hence a different window size may be superior to extract features in these situations. Alternatively, standardizing the tasks required from the participants could increase the algorithm performance, but it would lose ecological validity.

6.6.2 Clinical Considerations

This study demonstrated the feasibility of a novel means of tracking part of the external workload in water polo players. It showed that different classification approaches can obtain accurate predictions, and that one single sensor at the wrist is sufficient to investigate overhead throwing. Future research should aim to collect larger samples of subclasses of throws and passes for better classification performance. These can be used to further refine some of the parameters to train the model (i.e. window length). In the field, the authors recommend seeking alternative methods to mount the sensors such as sewing pockets into the bathing suits or using silicone sleeve on the wrist to hold the sensors in place rather than to tape them to the body. This decreases potential irritation to the skin from prolonged application, and will help to avoid loss of data from the sensors detaching from the athletes. Finally, analyses of workload can be compared with other health and sports performance indicators to monitor water polo players and optimize training and recovery cycles. As a key variable in the sports injury prediction cycle,[6] this overhead throwing workload can become fundamental in shoulder injury prevention strategies for water polo.

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Chapter 7. General discussion

7.1 Integration of findings into the sports injury pathway

In Chapter 1, the injury prevention pathway in its simplest form was described in four phases: establish the burden of injury, identify its mechanisms, plan interventions accordingly, and assess their effectiveness. Chapter 3, the systematic review of injuries in water polo aimed to accomplish this first phase. The review showed that most of the cohort data available comes from studies performed on national team players over short periods of time during the Olympic Games and aquatic world championships (approximately 4 weeks). Therefore, the prevalence of injuries described corresponds mainly to match injuries sustained in a competition environment. These injuries affect primarily the head and hands, with contradictory findings about concussions. Self-reported questionnaires as well as data from younger players indicates that shoulders are the area most prone to training complaints, mainly from overuse mechanisms. The studies of injury mechanisms focused almost exclusively on the shoulder, with only two studies designed to measure risk factors at baseline and follow-up with a cohort of players. In the group of injured athletes over the follow up, they observed significantly lower strength and overall range of motion of the shoulder at baseline. No other risk factor was explored in this fashion, indicating a gap of knowledge for the role of previous injury, scapular dyskinesis, throwing technique and workload in the injury pathway for this population.

Equipped with these insights, the next step in the injury prevention process should focus on identifying the risk factors for shoulder injuries. Given the use of both hand-held and isokinetic dynamometers to describe shoulder strength in water polo, it was necessary to first evaluate the level of agreement between these instruments. This was essential to compare the findings from future strength assessments in water polo players with previous literature. In Chapter 4, the technical report showed good concurrent validity between the values obtained with hand-held versus isokinetic dynamometry. However, the positive bias observed on Bland-Altman plots showed that ER and IR were consistently higher when measuring players on the isokinetic dynamometer than the hand-held dynamometer. The difference between the devices was also expressed in the ratios of ER over IR, showing no significant correlation between the two measurement methods. This study suggests that stronger players can be assessed more reliably using isokinetic dynamometry, but that the ranking of players on external or internal rotation alone is reliable with both methods. Given that previous studies of shoulder strength in water polo players consistently found them to be stronger than healthy controls, the findings from Chapter 4 inform a recommendation to use isokinetic dynamometers to measure strength in this population.

Chapter 5 was designed to investigate risk factors in a cohort study over the course of a full competition year. This aimed at providing evidence for step two of the injury prevention process: identify the underlying mechanisms. The risk factors included in the study design were history of a previous injury, shoulder rotators strength, shoulder range of motion, and static scapular upward rotation. The findings from this study identified history of previous injury, loss of shoulder IR range of motion, and increased scapular upward rotation as significantly different in the injured group compared with those that remained healthy during the nine month follow-up. Unlike previous findings, shoulder weakness was not significantly different between groups in this study. Instead, players with a history of injury showed significantly higher strength at baseline. In addition, male players exhibited significantly higher strength than their female counterparts, even when normalized by body weight. The female players showed greater overall shoulder range of motion on average than the male players. Altogether, the findings from this study show that all of the measured variables included had an association with injuries, albeit not in a linear fashion. In a complex systems approach to investigating shoulder injuries in water polo, the individual athlete determinants should include sex, player position, history of injuries, shoulder strength, range of motion, and scapular upward rotation. Further player variables that warrant investigation are throwing technique and workload. Preliminary evidence suggests that they belong in this web of determinants, but prospective studies are needed to confirm this hypothesis.

Finally, Chapter 6 describes a new methodology to measure external workload in water polo players. Inspired from the work of Wheeler et al (2013),[1] the main outcome variable was overhead throwing volume. The machine learning methods were successful in recognizing these activities compared to swimming, grappling and other tasks in training situations. Furthermore, the use of one single sensor yielded satisfactory results, suggesting that this setup is sufficient to calculate external workload in water polo. The observations of the patterns of accelerations and angular velocities of each subclass identified on the video analysis yielded important insights. The range of intensity for overhead throwing and passing is very large. This indicates that a much larger dataset will be necessary to identify subclasses of throwing and passing with sufficient accuracy for real-world applications.

7.2 Limitations of the thesis

The statistical models required to evaluate complex systems require very large datasets to power their analyses. In the context of this thesis, further differentiation between types of shoulder injuries might be necessary to bring together the correct risk factor variables. However, the number of water polo players competing at the international level is small in Canada. Although all of the national team players participated in this study, the statistical power of the findings remain limited. One method to increase the pool of participants would have been to include players from lower levels of competition. However, available evidence suggests that the injury patterns are different in these populations. Therefore, a correct statistical analysis would require a clustering of groups by competition level, and thus the power of the studies may not be significantly greater. Access to more participants of the same level would require international collaboration in large cluster studies.

In order to account for the expected changes in strength and flexibility that occur with training regimens, a periodical measurement of the risk factors in Chapter 5 could reveal different conclusions with a repeated-measure analysis. Unfortunately, this was not possible with the current cohort given limited availability to testing equipment with travelling participants. Strength was measured at a lower speed than that at which throwing occurs, therefore, the strength testing may not be an accurate representation of the muscle activity required to perform throwing tasks. Moreover, external rotators eccentrically contract during the throwing motion, which was not the mode tested in Chapter 5. Although the isokinetic dynamometer remains the gold standard, Chapter 4 did not compare this device with the same contraction mode as the hand-held device. The Spearman rank correlation analysis should decrease the bias in this situation, but this difference cannot be completely ignored in the conclusions.

Although scapular upward rotation was significantly greater in the injured group in Chapter 5, the three-degree difference between groups is close to the expected measurement error of this device. Therefore, the difference may be statistically significant, but it may not have a large clinical significance. Rather, this suggests that scapular alignment may be a contributing factor to injury risk, and clinicians should consider its assessment as part of their evaluation of water polo players. Recommendations based on these observations should follow a case-by-case evaluation of their findings. Moreover, the conclusions from a static evaluation of alignment may not be directly correlated with the observed changes in movement patterns related to throwing motions, and should be interpreted with caution.

Finally, the findings from Chapter 6 demonstrated that differentiation of overhead throwing between passing and shooting was difficult. This is expected based on the range of values of the data signals for each of the categories under study (see Figure 6.3). Therefore, the description of external workload in water polo in terms of counts of events alone may not be as informative as a measure that accounts for the intensity of the tasks performed. The inability for our equipment to record accelerations greater than 8g or angular speeds greater than 2000°/s may have limited the capture of peak values for some of the throwing motions. However, the data showed clipping, and the points where these cutoffs occurred were consistent in their patterns, which can be accounted for using the machine learning approaches utilized.

7.3 Clinical implications and future directions

The findings from this thesis highlight the importance of measuring risk factors regularly in an elite water polo population. Periodic health evaluations provide an ideal opportunity to make note of injury history for individual players, as well as to assess strength, range of motion, and scapular upward rotation. These variables interact to form a profile of athletes with a potentially higher risk of injury (model from Figure 1.1). Strength should be measured with an isokinetic dynamometer when available, as it remains more reliable to evaluate stronger individuals, and is still the gold standard approach. The ratios of ER over IR do not yield consistent relationships to injuries, leading us to believe that consideration of ER and IR separately is most important.[2] Agonists and antagonists work in different modes during the throwing motion, and perhaps different evaluations of these groups are necessary to identify a ratio that is more closely related to throwing injuries. Given that strength is a feature of interest in the development of water polo players, it should be measured at intervals that coincide with strength development cycles (i.e. 4-6 weeks). This information can reflect whether athletes are developing positive adaptations to the strength stimuli, or rather if important asymmetries or imbalances are observed. The findings from Chapter 5 showed that flexibility and scapular upward rotation may be the most important contributors to modifying injury risk. Therefore, these measurements should be taken regularly as well, with the focus of identifying loss of shoulder internal rotation compared to the non-dominant arm and asymmetries between dominant and non-dominant scapulae in upwards rotation. Clinicians can prescribe flexibility exercises to maintain internal rotation range of motion.[3] Further exercises aimed at scapular control can be efficient as well to ensure a solid pivot point for the gleno-humeral joint during overhead shooting and swimming tasks.[4]

Throughout the year, monitoring strategies can be put in place to obtain data on workloads as well. Internal load can be evaluated using session rate of perceived exertion and periodical wellness questionnaires.[5] External loads can be measured with submersible

IMU sensors, and machine learning approaches used to estimate overhead throwing activities. The counts of overhead throws can be documented as a measure of training volume for an individual session. Observing the changes in throw counts can serve as a proxy to evaluate the sudden increases in training load. Estimating the importance of an increase in load can be done by normalizing counts by the mean with the z-score distribution if the sample is large; otherwise, sport scientists can convert the scores to a t-distribution.[6,7] Another approach would consist in converting the counts as a ratio of acute load (i.e. last 7 days) over an accumulated chronic load (i.e. 28 days).[8,9] However, despite the popularity of this approach, questions still arise about its mathematical foundation, and these two concepts should likely remain uncoupled.[10,11] In the model presented in Figure 1.1, chronic load can act as a moderator to help decrease the risk of injury. Very sudden and large increases in acute load can however increase the risk of injury. Improvements to the methods described in Chapter 6 would consist of including an analysis of throwing intensity as well. This can be done as a secondary step after the raw data has been processed by the machine learning classifier. High-intensity activities can be counted as anything above the threshold of average peak accelerations for shots. Low-intensity activities can be counted as anything below the threshold of average peak accelerations for passes. Anything in between can thus be categorized as moderate intensity. An index of training or match intensity could thus be calculated by assigning a weight to each throw at each intensity level, similar to what has been proposed by Edwards with the summation of heart rate zones.[12] Early findings from basketball suggest that this weighted workload measurement based on plausible tissue capacity models is more closely associated with injury risk.[13]

Future research should attempt to reproduce the findings from Chapter 5 with a larger cohort of players. Countries with large player participation rates could include more participants, and cluster them by level (i.e. elite, sub-elite and recreational). A larger cohort would allow for time-to-event analyses and other statistical methods that can account for repeated injuries (i.e. generalized estimate equations).[11] In addition to the physical risk factors already investigated (range of motion, strength, scapular upward rotation), investigators should include daily monitoring of external load with IMU (both as volume and weighted intensity metric as described above). In order to base these future studies in strong conceptual foundations, attempts should be made to include measurements of psycho-social factors as well in the analysis of the injury pathways in water polo. This can be done with the inclusion of validated wellness questionnaires, administered either at regular intervals throughout the study or periodically with longer and more complete questionnaires. Once most confounders are measured, researchers can gain insight into the types of relationships between these variables and how they impact injury risk. Furthermore, the weight of these variables and their interactions can further be estimated with regression models, and help to identify the most important areas of concern for injury prevention strategies. Nevertheless, researchers must appreciate that complex systems demonstrate behaviors that are different than the sum of their individual parts, and that individual injury prevention strategies must be sought with an appreciation for the larger context in which they are to take place.

Chapter 8. Conclusion and summary

This dissertation aimed to assess the different risk factors related to shoulder injuries in water polo. A list of physical risk factors was first identified in a systematic review, indicating the role of strength, range of motion, scapular dyskinesis, training volume and shoulder proprioception in increasing the risk of developing new shoulder injuries. Strength measurements were compared between two common clinical devices, showing the superiority of the isokinetic dynamometer to measure shoulder strength in this population. A longitudinal study of shoulder injuries confirmed the association of previous history of injury, loss of internal rotation range of motion and scapular upward rotation with the incidence of new shoulder injuries. A method was further developed to count overhead throws automatically in training using inertial measurement units. Altogether, the results from this dissertation have identified key risk factors of shoulder injuries in water polo, and developed clinical tools to measure them over time. This provides researchers with the necessary foundation to perform more complex longitudinal studies within this sport in order to ascertain the interaction effects of these factors and their impact towards increasing injury risk.

8.1 Chapter 7-8 references

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Appendix

Table A3.4 Quality assessment of studies from Newcastle-Ottawa scales

Reference	**Newcastle-Ottawa Scale**	**Score**
Annett & al. (2000)	Cohort	8/9
Black & al. (2017)	Cohort	7/9
Blumenfeld et al. (2016)	Modified cross-sectional	6/10
Cunningham & Cunningham (1996)	Cohort	6/9
De Castro-Maqueda & Amar-Cantos (2019)	Modified cross-sectional	4/10
Ellapen et al. (2012)	Modified cross-sectional	6/10
Elliott. J (1993)	Modified cross-sectional	7/10
Engebretsen et al. (2013)	Cohort	8/9
Forrester (2020)	Cohort	6/9
Galic (2018)	Modified cross-sectional	6/10
Galluccio & al. (2017)	Modified cross-sectional	7/10
Giombini & al. (1997)	Modified cross-sectional	4/10
Goes et al (2020)	Modified cross-sectional	6/10
Gradidge et al. (2014)	Modified cross-sectional	6/10
Hame et al (2004)	Cohort	7/9
Hams et al (2019) "Epidemiology…"	Cohort	8/9
Hams et al. (2019) "Shoulder internal…"	Cohort	9/9
Hams et al. (2019) "Reduced shoulder…"	Cohort	9/9
Hersberger et al. (2012)	Modified cross-sectional	9/10
Jerolimov & Jagger (1997)	Modified cross-sectional	5/10
Junge et al. (2006)	Cohort	8/9
Junge & al. (2009)	Cohort	8/9
Kim & Park (2020)	Cohort	7/9
Klein et al. (2014)	Modified cross-sectional	10/10
Langner et al. (2020)	Modified cross-sectional	9/10
Macintosh et al. (1972)	Cohort	8/9

McLain & Reynolds (1989)	Cohort	6/9
Melchiorri et al. (2011)	Modified cross-sectional	7/10
Mountjoy et al. (2010)	Cohort	7/9
Mountjoy et al. (2015)	Cohort	8/9
Mountjoy, Miller & Junge (2019)	Cohort	7/9
Mukhtyar et al. (2014)	Modified cross-sectional	3/10
Prien et al. (2017)	Cohort	8/9
Rugg et al. (2019)	Cohort	9/9
Sallis et al. (2001)	Cohort	9/9
Soligard et al. (2017)	Cohort	8/9
Toohey et al (2019)	Cohort	9/9
Wheeler et al. (2013)	Modified cross-sectional	6/10
Whiting et al. (1985)	Modified cross-sectional	8/10
Youn et al. (2008)	Cohort	7/9
Zamora-Olave et al. (2018)	Modified cross-sectional	6/10

Table A3.5 List of all excluded articles with reason

Author	Year	Title	Reason for exclusion
Appleby, B	2012	The throwing shoulder: part 2. A review of the biomechanics and adaptation to overhead throwing	Review
Barrenetxea-Garcia, J., Torres-Unda, J., Esain, I. & al	2019	Anthropometry and isokinetic strength in water polo: Are young players ready to compete on adult teams?	No injury data
Bassano, A.	1995	Traumatologie oculaire en natation et water-polo	No injury data
Biener, K. and Keller, W.	1985	Sportunfaelle beim Wasserballspiel. / Sport accidents during water polo matches	Language
Brooks, J. M.	1999	Injuries in water polo	Review
Carrasco, M., Romero, E., Martínez, I. & al	2012	Incidencia y diagnóstico de las lesiones en un equipo de waterpolo de división de honor valenciana. / incidence and diagnosis of injuries in a valencia honor first division water polo team	Language
Cecchi, N. J., Monroe, D. C., Fote, G. M., & al	2019	Head impacts sustained by male collegiate water polo athletes	No injury data
Cecchi, N. J., Monroe, D. C., Phreaner, J. J. & al	2020	Patterns of head impact exposure in men's and women's collegiate club water polo	No injury data
Cecchi, N. J., Oros, T. J., Monroe & al	2019	The Effectiveness of Protective Headgear in Attenuating Ball-to-Forehead Impacts in Water Polo	No injury data
Chalmers, D. J. and Morrison, L.	2003	Epidemiology of non-submersion injuries in aquatic sporting and recreational activities	Review
Chorley, J., Eccles, R. E. and Scurfield, A.	2017	Care of shoulder pain in the overhead athlete	Review
Churchill, N. W., Hutchison, M. G., Graham, S. J. & al	2020	Neurometabolites and sport-related concussion: From acute injury to one year after medical clearance	No injury data
Colville, J. M. and Markman, B. S.	1999	Competitive water polo: Upper extremity injuries	Review
Crowley, E., Harrison, A. J. and Lyons, M.	2017	The Impact of Resistance Training on Swimming Performance: A Systematic Review	Review
Del Regno, C., Corona, K., Cerciello, S. & al	2014	Patello-femoral pain syndrome in water polo players	Design

Dion, JL, Padilla, R. and Piccininni, P.	2006	Diving into good dental health	No injury data
Drew, M. K. and Finch, C. F.	2016	The Relationship Between Training Load and Injury, Illness and Soreness: A Systematic and Literature Review	Review
Dugas, J., Chronister, J., Cain, E. L. & al	2014	Ulnar collateral ligament in the overhead athlete: A current review	Review
Edmonds, E. W. and Dengerink, D. D.	2014	Common conditions in the overhead athlete	Review
Eraslan, L., Yildiz, T. I., Tok, D. & al	2015	Assessment of two different pectoralis minor length measurements in relation with scapular kinematics in elite waterpolo players: Pilot study	No injury data
Feltner, M. E. and Taylor, G.	1997	Three-dimensional kinetics of the shoulder, elbow, and wrist during a penalty throw in water polo	No injury data
Fourre, J. M.	1977	Traumatologie du sport: water-polo	Review
Franic, M., Ivkovic, A. and Rudic, R.	2007	Injuries in water polo	Review
Freiwald, H. C., Schwarzbach, N. P. and Wolowski, A.	2021	Effects of competitive sports on temporomandibular dysfunction: a literature review	No injury data
Gkrilias, P., Matzaroglou, C., Kaloudis, A. & al	2019	Musculoskeletal disorders among Greek competitive water polo athletes	Design
Jobe, F. W., Giangarra, C. E., Kvitne, R. S. & al	1991	Anterior capsulolabral reconstruction of the shoulder in athletes in overhand sports	Design
Liang, M.	2008	Investigation and Research into the Injury and Disease of National Women's Water Polo Players	Language
Lupo, C., Capranica, L. and Tessitore, A.	2014	The validity of the session-[rate of perceived exhaustion] method for quantifying training load in water polo	No injury data
McMaster, W. C., Long, S. C. and Caiozzo, V. J.	1991	Isokinetic torque imbalances in the rotator cuff of the elite water polo player	No injury data
Merinu, J. A., Dragan, I., Escalas, F. & al	1981	Traumatic lesions in swimming, water polo and diving	Review
Miller, A. H., Evans, K., Adams, R. & al	2018	Shoulder injury in water polo: A systematic review of incidence and intrinsic risk factors	Review
Miller, J. W.	1999	Injuries and considerations in masters aquatics sports	Review

Monroe, D. C., Cecchi, N. J., Gerges, P. & al	2020	A Dose Relationship Between Brain Functional Connectivity and Cumulative Head Impact Exposure in Collegiate Water Polo Players	No injury data
Morrison, J.	1987	The current involvement of sports medicine with the Australian mens water polo team	No injury data
Mota, N. and Ribeiro, F.	2012	Association between shoulder proprioception and muscle strength in water polo players	No injury data
Mountjoy, M. and Junge, A.	2011	Preventing injuries in water polo: have we scored?	Design
Mountjoy, M., Junge, A., Slysz, J. & al	2019	An Uneven Playing Field: Athlete Injury, Illness, Load, and Daily Training Environment in the Year Before the FINA (Aquatics) World Championships, 2017	Review
Nichols, A. W.	2015	Medical Care of the Aquatics Athlete	Review
Oliveira, N. and Sanders, R. H.	2017	Effects of knee action phase and fatigue on Rectus Femoris and Biceps Femoris co-activation during the eggbeater kick	No injury data
Oliveira, N., Saunders, D. H. and Sanders, R. H.	2016	The Effect of Fatigue-Induced Changes in Eggbeater-Kick Kinematics on Performance and Risk of Injury	No injury data
Olivier, N. and Daussin, F.	2019	Isokinetic torque imbalances of shoulder of the french women's national water polo team	No injury data
Olivier, N. and Daussin, F. N.	2018	Relationships Between Isokinetic Shoulder Evaluation and Fitness Characteristics of Elite French Female Water-Polo Players	No injury data
Pacelli, L. C.	1991	Water polo's benefits surface	No injury data
Pashby, T.	1985	Eye injuries in sport	Design
Ramos, N., Youssefzadeh, K., Gerhardt, M. & al	2020	Results of hip arthroscopy in elite level water polo players with femoroacetabular impingement: return to play and patient satisfaction	No injury data
Rodineau, J.	2020	First anterior shoulder dislocation: Leading anatomic lesions?	Review
Sepet, E., Aren, G., Dogan Onur, O. & al	2014	Knowledge of sports participants about dental emergency procedures and the use of mouthguards	No injury data
Shea, K. P. and Folcik, M.	1989	Water sports injuries	Review
Spittler, J. and Keeling, J.	2016	Water Polo Injuries and Training Methods	Review

Stanford, A. and Lilley, D.	2007	Water polo	Design
Stromberg, J. D.	2017	Care of water polo players	Review
Szekely, G.	1996	A "Sydney 2000" programban reszt vevo sportolok klinikai vizsgalata. / Clinical check-up of young athletes participating in "Sydney 2000" program	Language
Tate, A., Turner, G. N., Knab, S. E. & al	2012	Risk factors associated with shoulder pain and disability across the lifespan of competitive swimmers	No injury data
Tooth, C., Gofflot, A., Schwartz, C. & al	2020	Risk Factors of Overuse Shoulder Injuries in Overhead Athletes: A Systematic Review	Design
Turgut, E., Yildiz, T. I., Demirci, S. & al	2018	Shoulder kinematics and mobility adaptations in water-polo players	No injury data
Turgut, E., Yildiz, T. I., Tok, D. & al	2015	Dynamic scapular position during arm abduction in water polo players	No injury data
Wallis, M. and Drew, M.	2014	Subsequent injury in women's water polo	Design
Wang, D., Rugg, C. M., Mayer, E. & al	2015	Predictors of orthopaedic surgery in NCAA athletes	Design
Webster, M. J., Morris, M. E. and Galna, B.	2009	Shoulder pain in water polo: A systematic review of the literature	Review
Witwer, A. and Sauers, E.	2006	Clinical measures of shoulder mobility in college water-polo players	No injury data
Yaghoubi, M., Esfehani, M. M., Hosseini, H. A. & al	2015	Comparative electromyography analysis of the upper extremity between inexperienced and elite water polo players during an overhead shot	No injury data
Zaremski, JL., Zeppieri Jr, G. and Tripp, B.L.	2019	Sport Specialization and Overuse Injuries in Adolescent Throwing Athletes: A Narrative Review	Review
Segawa, E., Komori, Y. & Hojo, T.	2017	The relationship between shoulder injuries and flexibility, shoulder range of motion characteristics in elite male Japanese water polo players	Language

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Wolters Kluwer

Support & Training   Feedback   Logged in as Felix Croteau at McGill University   Close

Database(s): **Ovid MEDLINE(R) ALL** 1946 to February 03, 2021

Search Strategy:

#	Searches	Results
1	waterpolo.mp.	15
2	water polo.mp.	329
3	1 or 2	342
4	pain.mp. or exp Pain/	828834
5	exp "Wounds and Injuries"/	920894
6	exp Athletic Injuries/	28047
7	(injury or injuries).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1202343
8	exp "Sprains and Strains"/	19142
9	(sprain or sprains).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	8971
10	(strain or strains).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	1023730
11	exp Brain Concussion/	9414
12	(concussion or concussions).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	13696
13	exp Eye Injuries/	22707
14	(eye injury or eye injuries).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	15849
15	exp Facial Injuries/	44579
16	exp Maxillofacial Injuries/	17012
17	(facial injury or facial injuries).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	7519
18	exp Tooth Injuries/	10430
19	(tooth injury or teeth injuries).mp. [mp=title, abstract, original title, name of substance word, subject heading word, floating sub-heading word, keyword heading word, organism supplementary concept word, protocol supplementary concept word, rare disease supplementary concept word, unique identifier, synonyms]	222
20	shoulder.mp. or exp Shoulder Dislocation/ or exp Shoulder Joint/ or exp Shoulder/ or exp Shoulder Impingement Syndrome/ or exp Shoulder Fractures/ or exp Shoulder Pain/	81028
21	scapula.mp. or exp Scapula/	11089
22	rotator cuff.mp. or exp Rotator Cuff/	14083
23	femoroacetabular impingement.mp. or exp Femoracetabular Impingement/	3080
24	4 or 5 or 6 or 7 or 8 or 9 or 10 or 11 or 12 or 13 or 14 or 15 or 16 or 17 or 18 or 19 or 20 or 21 or 22 or 23	3287027
25	3 and 24	116

Figure A3.2 Example of a search conducted in Medline

1Newcastle-Ottawa Scale adapted for cross-sectional studies

Selection: (Maximum 5 stars)

1) Representativeness of the sample:
   a) Truly representative of the average in the target population. * (all subjects or random sampling)
   b) Somewhat representative of the average in the target population. * (non-random sampling)
   c) Selected group of users.
   d) No description of the sampling strategy.

2) Sample size:
   a) Justified and satisfactory. *
   b) Not justified.

3) Non-respondents:
   a) Comparability between respondents and non-respondents characteristics is established, and the response rate is satisfactory. *
   b) The response rate is unsatisfactory, or the comparability between respondents and non-respondents is unsatisfactory.
   c) No description of the response rate or the characteristics of the responders and the non-responders.

4) Ascertainment of the exposure (risk factor):
   a) Validated measurement tool. **
   b) Non-validated measurement tool, but the tool is available or described.*
   c) No description of the measurement tool.

Comparability: (Maximum 2 stars)

1) The subjects in different outcome groups are comparable, based on the study design or analysis. Confounding factors are controlled.
   a) The study controls for the most important factor (select one). *
   b) The study control for any additional factor. *

Outcome: (Maximum 3 stars)

1) Assessment of the outcome:
   a) Independent blind assessment. **
   b) Record linkage. **
   c) Self report. *
   d) No description.

2) Statistical test:
   a) The statistical test used to analyze the data is clearly described and appropriate, and the measurement of the association is presented, including confidence intervals and the probability level (p value). *
   b) The statistical test is not appropriate, not described or incomplete.

This scale has been adapted from the Newcastle-Ottawa Quality Assessment Scale for cohort studies to perform a quality assessment of cross-sectional studies for the systematic review, "Are Healthcare Workers' Intentions to Vaccinate Related to their Knowledge, Beliefs and Attitudes? A Systematic Review".

We have not selected one factor that is the most important for comparability, because the variables are not the same in each study. Thus, the principal factor should be identified for each study.

In our scale, we have specifically assigned one star for self-reported outcomes, because our study measures the intention to vaccinate. Two stars are given to the studies that assess the outcome with independent blind observers or with vaccination records, because these methods measure the practice of vaccination, which is the result of true intention.

Figure A3.3 Newcastle-Ottawa Scale

NEWCASTLE - OTTAWA QUALITY ASSESSMENT SCALE
COHORT STUDIES

<u>Note</u>: A study can be awarded a maximum of one star for each numbered item within the Selection and Outcome categories. A maximum of two stars can be given for Comparability

Selection

1) <u>Representativeness of the exposed cohort</u>
   a) truly representative of the average water polo players in the community ✱
   b) somewhat representative of the average water polo players in the community ✱
   c) selected group of users eg nurses, volunteers
   d) no description of the derivation of the cohort

2) <u>Selection of the non exposed cohort</u>
   a) drawn from the same community as the exposed cohort ✱
   b) drawn from a different source
   c) no description of the derivation of the non exposed cohort

3) <u>Ascertainment of exposure</u>
   a) secure record (eg surgical records) ✱
   b) structured interview ✱
   c) written self report
   d) no description

4) <u>Demonstration that outcome of interest was not present at start of study</u>
   a) yes ✱
   b) no

Comparability

1) <u>Comparability of cohorts on the basis of the design or analysis</u>
   a) study controls for the most important factor ✱
   b) study controls for any additional factor ✱ (This criteria could be modified to indicate specific control for a second important factor.)

Outcome

1) <u>Assessment of outcome</u>
   a) independent blind assessment ✱
   b) record linkage ✱
   c) self report
   d) no description

2) <u>Was follow-up long enough for outcomes to occur</u>
   a) yes (select an adequate follow up period for outcome of interest) ✱
   b) no

3) <u>Adequacy of follow up of cohorts</u>
   a) complete follow up - all subjects accounted for ✱
   b) subjects lost to follow up unlikely to introduce bias - small number lost - > ____ % (select an adequate %) follow up, or description provided of those lost) ✱
   c) follow up rate < ____% (select an adequate %) and no description of those lost
   d) no statement

Figure A3.4 Newcastle-Ottawa Scale for Cohort Studies

Table A4.4 Strength factors comparison between males and females

Variable		Male (n=19)	Female (n=20)	Wilcoxon (p-value)	Hedge's G effect size [95% CI]
Isometric torque dominant shoulder	ER (kg·F·m)	23.2	15.2	<0.01	2.40 [1.57,3.24]
	IR (kg·F·m)	29.4	19.6	<0.01	1.89 [1.13,2.66]
	ER/IR ratio	0.81	0.77	0.46	0.30 [-0.34,0.93]
Isometric torque non-dominant shoulder	ER (kg·F·m)	22.0	14.3	<0.01	2.60 [1.73,3.46]
	IR (kg·F·m)	28.5	19.4	<0.01	2.13 [1.33,2.93]
	ER/IR ratio*	0.78	0.74	0.41	0.38 [-0.26,1.02]
Isokinetic torque dominant shoulder*	ER (N·m)	44.9	24.3	<0.01	2.84 [1.92,3.75]
	IR (N·m)	63.5	34.8	<0.01	2.93 [2.00,3.86]
	ER/IR ratio	0.71	0.70	0.85	0.06 [-0.58,0.71]
Isokinetic torque non-dominant shoulder*	ER (N·m)	44.7	24.3	<0.01	3.10 [2.14,4.06]
	IR (N·m)	61.9	34.6	<0.01	2.35 [1.51,3.19]
	ER/IR ratio	0.74	0.71	0.47	0.25 [-0.39,0.90]
Relative isometric torque dominant shoulder	ER (kg·F·m/kg)	0.25	0.21	<0.01	1.19 [0.50,1.88]
	IR (kg·F·m/kg)	0.32	0.27	0.01	0.96 [0.29,1.64]
Relative isometric torque non-dominant shoulder	ER (kg·F·m/kg)	0.24	0.19	<0.01	1.25 [0.56,1.95]
	IR (kg·F·m/kg)	0.31	0.26	0.01	0.90 [0.23,1.57]
Relative isokinetic torque dominant shoulder*	ER (N·m/kg)	0.48	0.33	<0.01	2.03 [1.24,2.83]
	IR (N·m/kg)	0.68	0.48	<0.01	2.00 [1.21,2.79]
Relative isometric torque dominant shoulder	ER (kg·F·m/kg)	0.25	0.21	<0.01	1.19 [0.50,1.88]
	IR (kg·F·m/kg)	0.32	0.27	0.01	0.96 [0.29,1.64]

*Isokinetic measurements exclude one female participant who did not complete the test task

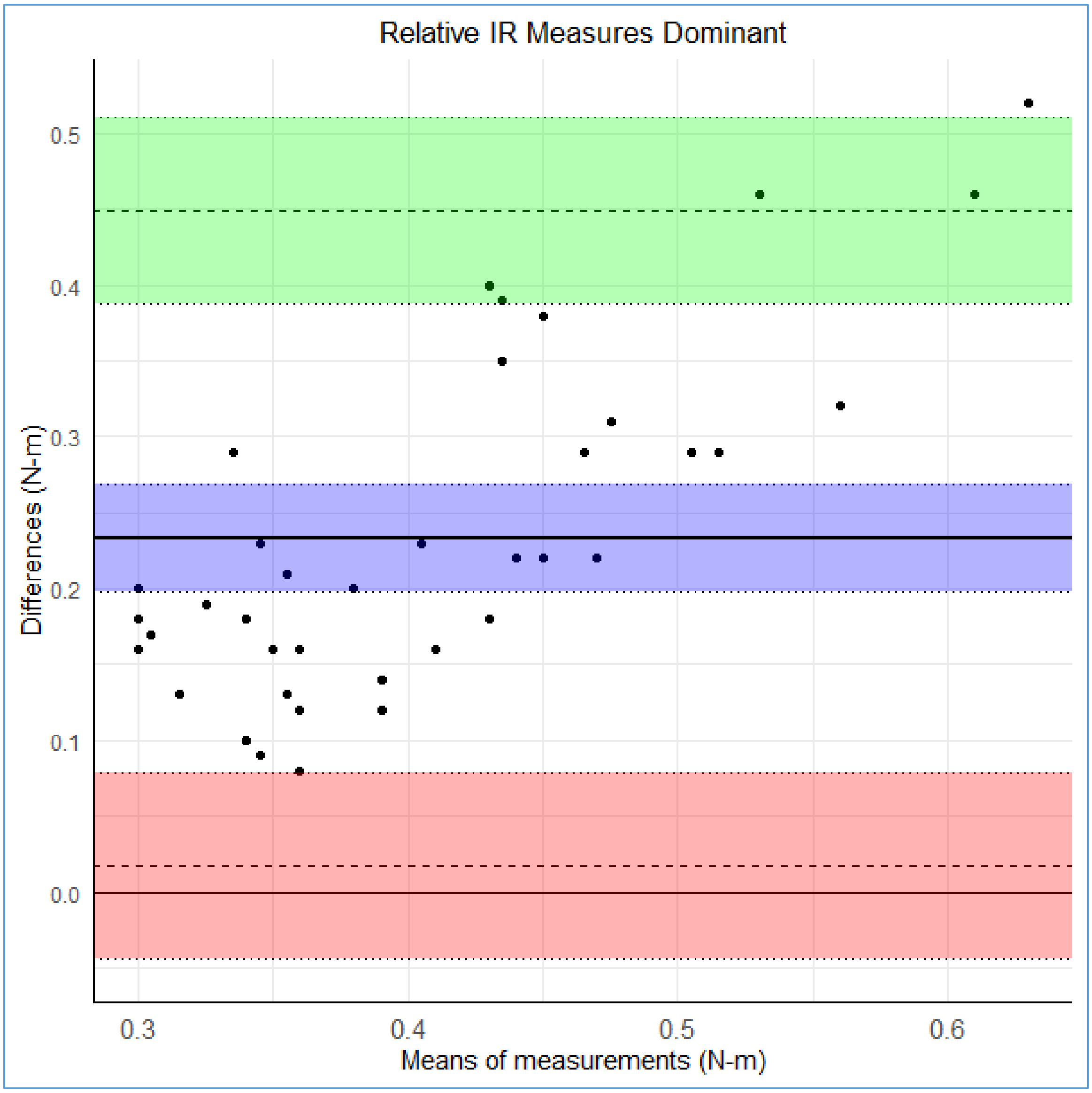

Figure A4.4 Bland-Altman plots for dominant shoulder internal rotation. The bias line is in the center, with the upper and lower limits of agreement with their 95% confidence intervals in green and red respectively. The shape of the plot shows that as the strength values increase, so does the difference between the two methods.

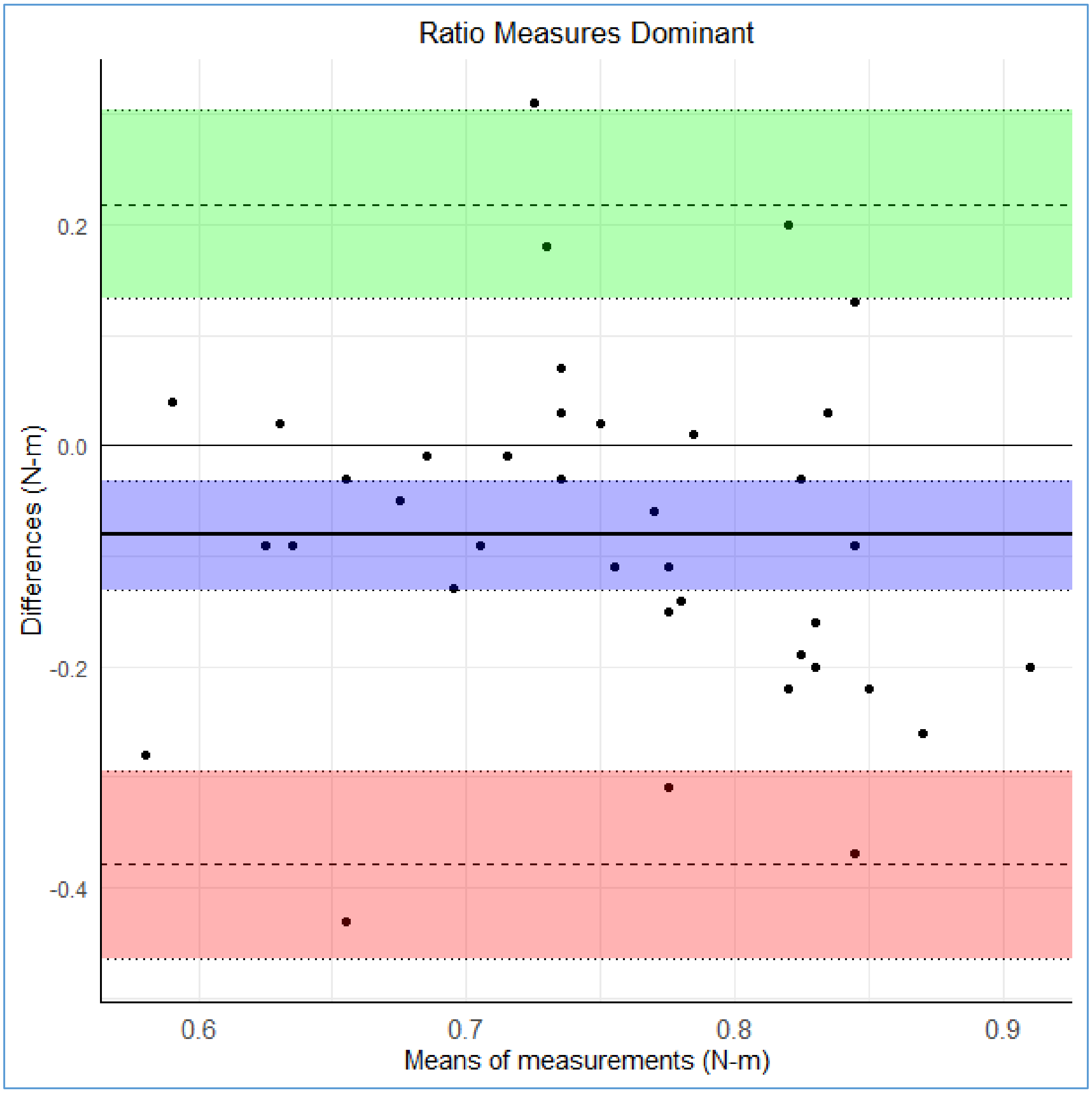

Figure A4.5 Bland-Altman plots for dominant shoulder ER/IR ratios. The bias line is in the center, with the upper and lower limits of agreement with their 95% confidence intervals in green and red respectively. The shape of the plot does not demonstrate the same heteroscedasticity between variables.

Table A5.5 Physical factors comparison dominant males and females (independent t-test)

Variable		Male (n=19)	Female (n=20)	Significance (p-value)	Effect size *g* [95% CI]
Isokinetic relative strength dominant shoulder*	ER (Nm/kg)	0.48 (0.09)	0.33 (0.04)	<0.01	2.03 [1.26, 2.82]
	IR (Nm/kg)	0.68 (0.13)	0.47 (0.07)	<0.01	2.04 [1.26, 2.83]
	ER/IR ratio	0.71 (0.11)	0.71 (0.10)	0.99	-0.01 [-0.64, 0.63]
Dominant shoulder range of motion	ER (°)	102.6 (10.2)	107.3 (11.8)	0.19	-0.42 [-1.06, 0.22]
	IR (°)	49.9 (10.7)	55.0 (10.8)	0.15	-0.46 [-1.11, 0.18]
	Total rotation (°)	152.4 (12.4)	162.2 (13.2)	0.02	-0.75 [-1.41, -0.09]
	ER gain (°)	8.2 (7.7)	4.6 (8.9)	0.17	0.42 [-0.22, 1.07]
	IR loss (°)	8.7 (7.0)	5.0 (8.7)	0.18	0.42 [-0.22, 1.07]
Scapula	Upward rotation (°)	12.7 (3.5)	10.7 (3.0)	0.07	0.59 [-0.06, 1.24]

*Strength variables were not normally distributed and groups were compared with Mann-Whitney test

McGill

Faculty of Medicine
3655 Promenade Sir William Osler #633
Montreal, QC H3G 1Y6

Faculté de médecine
3655, Promenade Sir William Osler #633
Montréal, QC H3G 1Y6

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At a full Board meeting on 15 April 2019, the Faculty of Medicine Institutional Review Board, consisting of:

Frances Aboud, PhD	John Breitner, MD
Kelly Davison, MD	Patricia Dobkin, PhD
Carolyn Ells, PhD	Sally Mann, M.S.
Alexandra Pasca, LL.M.	Blossom Shaffer, MBA
Maida Sewitch, PhD	Margaret Swaine, BA

Examined the research project **A04-M16-19B** titled: *Role of strength and flexibility in shoulder injuries in water polo*

As proposed by: Shawn Robbins (Applicant) to ______ (Granting Agency, if any)

And consider the experimental procedures to be acceptable on ethical grounds for research involving human subjects.

21 May 2019
Date

Chair, IRB

Dean/Associate Dean

Institutional Review Board Assurance Number: FWA 00004545

Figure A9.1 Ethics certificate for risk factors study

McGill

Faculty of Medicine
3655 Promenade Sir William Osler #633
Montreal, QC H3G 1Y6

Faculté de médecine
3655, Promenade Sir William Osler #633
Montréal, QC H3G 1Y6

Fax/Télécopieur: (514) 398-3870
Tél/Tel: (514) 398-3124

07 February 2020

Dr. Shawn Robbins
School of Physical and Occupational Therapy
Davis House
3654 Promenade Sir William Osler
Montreal QC H3G 1Y5

Info-Ed File Number: **19-12-024** **(IRB Internal Study Number:** A01-M01-20A**)**

Study/Protocol Title: *Monitoring training load using inertial measurement units in water polo*

Principal Investigator: Shawn Robbins; Félix Croteau

Sponsor Name (if applicable): INS Québec: Research, Innovation and Dissemination of Information Program (PRIDI)

Dear Dr/Professor Robbins,

At a full Board meeting on 13 January 2020, the Faculty of Medicine Institutional Review Board examined the above-referenced research project and considered the experimental procedures acceptable and in adherence to the ethical requirements for research involving human subjects.

Final ethics approval was granted on 07 February 2020. **The ethics certificate is valid until 12 January 2021.**

The following documents were reviewed and approved:

- Study Protocol (including Appendices A, A2, B, C, C2, D, D2, E, E2, F, G, G2), IRB dated version January 2020;
- Participant Consent Form, IRB dated version January 2020;
- Participant Consent Form: Video-recordings, IRB dated version February 2020.

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The Principal Investigator is required to immediately notify the Institutional Review Board Office, via amendment or progress report, of:

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- Any significant changes to the research project and the reason for that change, including an indication of ethical implications (if any);
- Serious Adverse Effects experienced by participants and the action taken to address those effects;
- Any other unforeseen events or unanticipated developments that merit notification;
- The inability of the Principal Investigator to continue in her/his role, or any other change in research personnel involved in the project;
- A delay of more than 12 months in the commencement of the research project, and;
- Termination or closure of the research project.

The Principal Investigator is required to submit an annual progress report (continuing review application) on the anniversary of the date of the initial approval (or see the date of expiration).

The Faculty of Medicine IRB may conduct an audit of the research project at any time.

If the research project involves multiple study sites, the Principal Investigator is required to report all IRB approvals and approved study documents to the appropriate Research Ethics Office (REO) or delegated authority for the participating study sites. Appropriate authorization from each study site must be obtained before the study recruitment and/or testing can begin at that site. Research funds linked to this research project may be withheld and/or the study data may be revoked if the Principal Investigator fails to comply with this requirement. A copy of the study site authorization should be submitted the IRB Office.

It is the Principal Investigator's responsibility to ensure that all researchers associated with this project are aware of the conditions of approval and which documents have been approved.

The McGill IRB wishes you and your colleagues every success in your research.

Roberta Palmour, PhD
Chair
Institutional Review Board

Please quote the IRB Study Number and title in all correspondence.

Cc: Associate Dean, Research (Medicine)

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Figure A9.2 Ethics certificate for IMU study

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Author names (in order of authorship): Félix Croteau, Shawn Robbins, David Pearsall

Manuscript Title: Hand-held shoulder strength measures correlate with isokinetic dynamometry in elite water polo players

Manuscript Number: ______

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