Sex differences in shoulder muscle activation and fatigue among elite water polo players

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CONTRIBUTION OF AUTHORS

Lily Dong, the candidate, was responsible for research setup, recruitment, data collection, analysis, writing, and any other steps necessary for the completion of the research study and submission of the thesis as per McGill University requirements.

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Geneviève Gill, B.Sc., assisted during data collection, and Chris Bailey, M.Sc., provided guidance during data analysis.

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ABSTRACT

The goal of this Master's project was to use electromyography (EMG) to explore sex-specific shoulder muscle activation and fatigue responses among elite water polo athletes. A secondary aim was to identify if sex differences in lean bodyweight could explain sex differences in strength-related performance measures. Highly trained female and male water polo players performed maximal voluntary contractions of shoulder external and internal rotation, as well as maximal throws of a water polo ball from a seated position on land. They then completed a repetitive shoulder internal rotation task until they could no longer maintain 50% of their individual peak torque, or until they reported a rating of perceived exertion of 8 or more on the Borg CR10 scale. Immediately following this fatiguing task, participants repeated the maximal external rotations, internal rotations, and ball throws. Shoulder rotation torque was quantified using an isokinetic dynamometer, and EMG was measured using surface bipolar electrodes. Results indicated that females and males had mostly similar muscle activation and fatigue responses during maximal internal rotation and seated throwing, but that middle trapezius EMG root mean square and median power frequency measures and fatigue responses were sex-dependent. Both groups also demonstrated increased functional connectivity among muscle pairs after fatigue. Interestingly, though lean bodyweight accounted for sex differences in internal rotation strength and ball throw velocity, it did not explain external rotation strength differences between females and males. Findings suggest that for the muscles we investigated, females and males have shared muscle activations and fatigue adaptations, but there are still sex-specific responses that could be linked to different motor strategies.

RÉSUMÉ

Le but de ce projet de maîtrise était d'utiliser l'électromyographie (EMG) pour explorer l'activation musculaire et les réponses à la fatigue de l'épaule, ainsi que comment ces paramètres varient selon le sexe, parmi des athlètes élites en water-polo. Un objectif secondaire était d'identifier si les différences entre les sexes dans leur masse corporelle maigre pourraient expliquer les différences entre les groupes dans des mesures de performance liées à la force. Des joueurs et joueuses élites de water-polo ont exécuté des contractions volontaires maximales en rotation externe et interne de l'épaule suivies par des lancers maximaux d'un ballon de water-polo dans une position assise. Ils ont ensuite effectué une tâche répétitive de rotation interne de l'épaule jusqu'à ce qu'ils ne puissent pas maintenir 50% de leur effort maximal volontaire ou lorsqu'ils signalent un 8 ou plus sur l'échelle Borg CR10. Les participants ont immédiatement répété les rotations externes, rotations internes et lancers maximaux. Les efforts de rotation de l'épaule étaient quantifiés à l'aide d'un dynamomètre isocinétique, et l'activité des muscles était mesurée à l'aide d'électrodes bipolaires de surface. Les résultats indiquent que dans l'ensemble, les femmes et les hommes avaient des activations musculaires et des réponses à la fatigue similaires pendant les rotations internes et les lancers, mais que les mesures et les réponses à la fatigue de la valeur quadratique moyenne et de la fréquence de la force moyenne de l'EMG du trapèze médian variaient selon le sexe. Après la fatigue, les deux groupes ont aussi partagé une augmentation de connectivité fonctionnelle parmi des paires de muscles. Il est intéressant de noter que bien que la masse corporelle maigre explique les différences entre les sexes dans la force de rotation interne et dans la vitesse du lancer, elle n'a pas pu expliquer les différences observées entres les joueurs et joueuses dans leur force de rotation externe. Ces résultats suggèrent que, pour les muscles étudiés, les femmes et les hommes partagent certaines activations musculaires et adaptations à la fatigue, mais qu'il existe néanmoins des différences entre les sexes dans leurs réponses musculaires qui pourraient être liées à de différentes stratégies motrices.

TABLE OF CONTENTS

INTRODUCTION

Recently, it has become clear that results from research on males cannot – and should not – be assumed to be valid for females, and requirements for researchers to include both sexes have become more explicit. Though efforts are being made to involve female participants, sports science research is just one domain in which females are still underrepresented.[1] In examining 1382 articles in major sports and exercise medicine journals, Costello et al.[1] found that females accounted for an average of 35-37% of participants. However, the benefits of including both females and males and actively comparing sex differences can be far-reaching, with implications for sex-specific injury prevention, performance, and participation.

Water polo is a fast-moving sport in which athletes tax their shoulders in repetitive passing and shooting, as well as in swimming, covering upwards of 1000m per game.[2, 3] Unsurprisingly, the shoulder is the most common site of all injuries among water polo players.[4] Furthermore, most shoulder injuries are overuse injuries,[4] resulting from the combined effects of throwing, swimming, and overhead defending.[5, 6] Studies on swimmers[7] and handball players[8, 9] show that females have higher rates of shoulder problems than males. However, in water polo, while females have reported more shoulder injuries,[10] there are limited studies comparing shoulder injury incidence between males and females and the research remains inconclusive about whether sex-specific predispositions exist.

Sex comparisons during lower limb movements serve as an example of the importance of having sex-specific dimensions in research. It has been shown that females and males demonstrate different muscle activation patterns in soccer kicks,[11] countermovement jumps,[12, 13] jump landings,[12, 14] and cutting maneuvers.[14, 15] These findings have helped explain the higher female risk of anterior cruciate ligament (ACL) injuries and subsequently, guide effective injury prevention strategies.[16] There has been, however, much less substantive research on whether there are similar sex-specific phenomena in mechanisms of sport-related upper limb injury. The existing literature comparing throwing between the sexes has focused on kinematics or performance outcomes, like ball velocity.[17-19] By investigating the neuromuscular aspect of movement control, e.g. the activation and coordination of muscles, we may bring a new perspective to explain why females and males exhibit different injury rates and/or movement patterns when performing the same task.

Another element to consider is the role of muscular fatigue in movement control, particularly because athletes are often able to maintain performance despite the presence of fatigue. Although altering muscle activation and coordination strategies could have short-term performance benefits, these adaptations may promote future injury. So far, the influence of fatigue on neuromuscular parameters of the upper limb, and how it may differ between sexes, represents a largely untouched area in sports-specific research. In the workplace, females have reported more neck and shoulder injuries[20] and research on repetitive work-related upper limb tasks have indicated that neuromuscular sex differences do indeed exist, even when females and males share identical performance outcomes. Because of how neuromuscular strategies vary depending on the task, intensity, and type of contraction,[21] those results, acquired from low-intensity, controlled movements, strengthen the argument that research specifically addressing unrestricted, maximal upper limb movements is needed to understand sport-specific sex differences in muscle activation.

The objective of this thesis was thus to compare elite female and male water polo athletes in their shoulder muscle activation and fatigue response during maximal shoulder rotations and throwing. A secondary aim was to investigate the influence of lean bodyweight on sex differences in torque production capacity and throwing velocity. We hypothesized that females and males would have different muscle activations and that females would have higher levels of functional connectivity. We also predicted that during maximal shoulder efforts, males would producer greater torque and throwing velocities, and that this would be related to their higher percentage of lean bodyweight. Finally, we expected that the effects of fatigue on these neuromuscular and performance parameters would differ by sex. The results of this research will provide a better understanding of sex differences during a sport-specific upper limb task and could ultimately contribute in revealing sex-specific mechanisms related to the development of shoulder injuries.

LITERATURE REVIEW

Shoulder Injuries in Water Polo

The shoulder girdle is composed of the sternoclavicular, acromioclavicular, scapulothoracic, and glenohumeral joints. The interacting nature of the joints and the various degrees of freedom available give the shoulder its remarkable mobility. This extensive joint range of motion comes, however, at the cost of stability. Connective tissue stiffness, scapular positioning, and neuromuscular activation must all integrate to protect the structures that run through the shoulder and to ensure healthy shoulder function.[22]

Athletes engaged in sports characterized by predominantly overhead movements, especially forceful ones such as throwing, are particularly susceptible to shoulder injuries. [6, 23, 24] Throwing subjects the shoulder to enormous forces at tremendous angular velocities, and repetitive applications of these high forces result in structural changes that jeopardize muscle agonist-antagonist balances and the normal kinematics of the shoulder, consequently predisposing the athlete to shoulder injury.[6, 24]

Altered kinematics resulting from overuse, fatigue, or laxity are also a primary contributor to the ubiquity of shoulder injuries among swimmers.[25] Because of the pool sport setting, risk factors for water polo players are often – incorrectly – presumed to be the same as those for swimmers.[4, 26] The swim strokes performed in water polo, however, are tailored to the particular demands of the sport: in order to keep their eyes on the ball, other players, and to be constantly ready to respond to game play, water polo players employ head-up swimming postures.[26] This adaptation means that players are not able to perform the body roll present in conventional freestyle swimming.[27] This forces the athlete to use shorter strokes with high elbows, putting the shoulder into increased abduction and internal rotation, increasing early fatigue of the rotator cuff, and thereby potentially resulting in posterior impingement.[27]

A dynamic, high-intensity team sport, water polo also involves repetitive, forceful passing and throwing. Kinematic modelling based on male collegiate water polo players demonstrated that elbow extension and trunk rotation were the largest contributors to predicted ball speed.[28] However, though the throwing motion of water polo players resembles quite closely that of other overhead sports,[28] the constraints imposed by the aquatic environment – namely the lack of a solid base of support – increase the demand on the shoulder joint.[5] Though average ball velocities in water polo (15-20m/s)[29] are much lower than for baseball pitches (34-38m/s)[30] and football passes (21m/s),[31] the water restricts water polo players' ability to use a proximal-to-distal throwing sequence and employ optimal trunk rotation[5], and as a result, joint torques at the shoulder are actually similar to those of other land athletes.[31] This combination of repetitive throwing, high volumes of swimming in an altered posture, as well as overhead defending create stress on the shoulder at the extremes of its range of motion.[4, 26]

Indeed, the shoulder is the most common site of injury among water polo players.[4] A recent review of existing literature reported that rates of shoulder pain and injury are between 24-51% among male players,[4] with one study reporting incidence rates as high as 80%.[27] A study that used ultrasound to image the shoulders of male players in Italy's elite and minor water polo leagues found that 38 of the 42 players displayed shoulder injuries or alterations in shoulder structures – this despite only 13 actually reporting shoulder pain, with the rest of the athletes being asymptomatic.[32] Findings that the majority of shoulder injuries were of insidious onset[4] support previous evidence that shoulder injury in water polo are often overuse injuries that result from the collective effects of throwing, swimming, and defending.[5, 6]

Sex Differences in Shoulder Injury Incidence

A study by Prien et al.[33] comparing injuries and illnesses that occurred during the 2009, 2013, and 2015 FINA World Championships, found that the incidence of all reported injuries had increased over time, and that across aquatic disciplines, the shoulder was the most commonly affected site.[33] They also examined injuries in the four weeks leading up to the 2015 Championships, and concluded that both before and during competition, the most common causes of injury were overuse and traumatic contact but that there was no discipline-specific gender effect on the injury.[33] However, men sustain more contact injuries than women during gameplay[34] and because injuries were not separated by type (overuse vs. traumatic contact) within each discipline, this could have masked an overrepresentation of female overuse injury – which is present in other sports.[7, 35] It may be more important, though, to consider injuries sustained outside of competition: in water polo, twice as many shoulder injuries occur during general pool training than during game play.[4] An analysis of retrospective self-report injury data from sub-elite male and female water polo athletes found no significant sex difference in the incidence of shoulder injury reported in a five-year period (38% of males and 49% of females), but again, the researchers did not control for insidious versus traumatic mechanisms of injury when comparing sexes.[4] The authors also cautioned to interpret findings with discretion, citing missing self-report data from the male group and limitations to available data.[4] In another study, researchers did find a sex difference.[10] Using a standardized injury form to record almost 2000 injuries over 15 seasons, authors found that female water polo players had significantly more shoulder injuries than males (8.09 injuries per 100 participant years vs. 3.40 for men), though they attributed this discrepancy to a more intense training regimen.[10] Thus, in water polo, there is yet to be a study that compares sex differences in shoulder injury rate while controlling for training and competition volume and/or mechanism of injury; in this circumstance, it remains inconclusive whether there are sex-specific risk factors.

Results from other overhead sports indicate that females may indeed be at an increased risk of overuse shoulder problems. Among youth swimmers, females suffered from significantly more shoulder pain,[36] and data from the NCAA Injury Surveillance Program from 2009-2014 showed that while there was no sex difference in the overall rate of injury in swimming, females suffered a higher rate of overuse injury.[7] Female adolescent handball players,[8] as well as female elite handball players,[9] had significantly higher rates of shoulder problems in general, and of shoulder problems labelled as "substantial", compared to their male counterparts. In water polo, a sport that combines both swimming and considerable throwing – the latter of which is suspected to be the most influential on shoulder mobility changes[5] – sex-specific shoulder injury trends may well follow a similar pattern.

Sex Differences in Throwing

In a study using 3-dimensional video analysis, Elliott & Armour[37] compared the penalty throw among 6 female and 6 male water polo players. The male players, who were taller, heavier, and had larger limb lengths and girths than the females, produced significantly greater ball velocities.[37] The authors observed multiple differences in joint angles and movement timing, such as females having a more vertical vs. horizontal backswing, possibly due to a more square position relative to the net and thus less hip and shoulder rotation; females initiating elbow extension earlier in the forward swing; males demonstrating a wrist extension phase prior to final wrist flexion; and females releasing the ball at an almost vertical forearm position, as opposed to the more forward inclined position of the males. Elliott & Armour[37] suggested that the smaller hand-to-ball ratio of the women was an important factor in the technical differences that, in turn, could explain the difference in ball velocity. It is important to note that though both groups were high-level athletes, it was indicated that the males were of higher throwing standard.[37]

Men generating faster ball velocities in throwing movements is a consistent finding, and in other sports, researchers have also tried to identify technical sex differences.[17-19, 38, 39] Serrien et al.[18] found kinematic differences between females and males in the handball standing throw with run up in the phases preceding ball release, and that the different throw patterns exhibited by males and females could be linked to sex-specific anthropometric profiles. In a cross-sectional study of throwing among male and female competitive handball athletes between 6-16 years of age, Gromeier et al.[40] found that while the humerus and forearm movements were similar between sexes, the preparatory phases, which included stepping, trunk rotation, and backswing, were different. Interestingly, quantitative performance, measured as throw accuracy, did not differ between sexes despite their technical differences.[40] When Chu et al.[17] compared overhand baseball pitches between elite amateur female and male pitchers, they also found sex differences in kinematic and temporal parameters, including lower peak angular velocity of elbow extension and longer time between foot contact and ball release among females. The authors suggested that the dissimilarities they observed could not completely be explained by sex differences in height, weight, and shoulder and elbow joint torques, though they did not elaborate on other potential factors.[17] In javelin throwing, Liu et al.[41] analyzed throw timing and found that elite females and males possessed different sequencing techniques for the initiation of lower and upper extremity segment and joint angular motions – despite these initiation techniques resulting in similar sequencing patterns for maximum joint centre linear velocities. There are some researchers, however, who have attributed the sex difference in ball velocity to men having higher levels of fat-free mass, rather than to differences in technique.[19] Van den Tillaar & Cabri[19] compared the kinematics of overarm throwing among elite handball players and found there to be no significant differences in maximal joint angular velocities and segment angles at ball release. This prompted them to support the notion that elite male and female handball players have similar throwing kinematics and that differences in ball velocity could be explained by height and muscle mass.[19] Overall, it appears that although sex differences in strength are a critical factor in the velocity of the projectile, there may be other details that distinguish males and females, and in many throwing movements, females and males may achieve similar performance (e.g. accuracy) without using identical movement strategies. Kinematic comparison has often been used to compare the sexes, but investigating muscle activation may present additional insight, particularly if movement kinematics and/or output *are* similar.

Electromyography

Electromyography (EMG) is a method used to quantify the electrical activity of the muscle. Surface EMG involves the non-invasive application of electrodes to the skin to record the electrical activity of the underlying muscle. The amplitude of the EMG signal, often quantified as the root-mean-square (RMS) of the signal, in part reflects motor unit recruitment and rate coding[42, 43] and is used to interpret the level of muscle activation. In breaking down the EMG signal into its frequency contents, it is possible to determine the power distribution of frequencies and calculate the median power frequency (MdPF), which is related to the conduction velocity of motor action potentials on the muscle membrane. When considering more than one muscle, mutual information can be determined. Unlike correlation measures, mutual information can measure both linear and nonlinear relationships between time series of two muscles.[44] Mutual information between muscles represents the shared information and is a measure of functional connectivity.[45, 46] It can be compared across different muscle pairs or separate measurements by normalizing it to a range of 0 to 1, with a normalized mutual information (NMI) of 0 indicating the two muscles are independent and an NMI of 1 indicating functional dependence.[47]

Electromyography in Lower Limb Injury Prevention

There is a lack of studies that use EMG to investigate sex differences during throwing or other unrestricted explosive movements of the upper extremity. In the lower limb, however, males and females have demonstrated different muscle activity patterns when performing maximal, unconstrained, and sport-related movements. Among recreationally active students performing maximal countermovement jumps, males had more rectus femoris activity and females had more ankle co-activation in the concentric phase.[12] When researchers examined high-level collegiate soccer players who performed soccer kicks, females and males, despite sharing similar ball velocities and phase timings, differed both kinematically and in their muscle activation.[11] The same population has also demonstrated different leg muscle activation in side-step cutting.[15] When playing the same sports, females experience 4-6x more anterior cruciate ligament (ACL) injuries than males, and though the reasons are multifactorial, our knowledge about females presenting less hip abduction[11] and greater quadriceps activation relative to their hamstrings[15] has been pivotal in understanding why females are at greater risk. This has in turn resulted in the development of sex-specific neuromuscular interventions that are effective in reducing injury risk among females.[16]

In addition to providing information on muscle activity, EMG can also be used to determine if a muscle is fatigued. Changes in muscle activation and coordination under conditions of fatigue are of interest because of the role fatigue plays in injury risk.

Fatigue

Muscular fatigue is the exercise-induced temporary loss of maximal power output[48] and is accompanied by an increase in perceived effort.[49] Fatigue occurs through various different mechanisms that are categorized into peripheral or central components, depending on the level of the motor pathway at which it occurs.[50, 51] Peripheral fatigue derives from changes at or distal to the neuromuscular junction,[52] such as unmet demands for ATP due to insufficient oxygen availability in the working muscle.[53] Central fatigue results from processes originating within the central nervous system that decrease neural drive to the muscle.[51] In activities of submaximal intensity, the point at which there is a decrease in maximal force generation capacity is not as easily discerned, with fatigue often becoming apparent later, when the original intensity of the activity can no longer be sustained.[54] This point is identified as exhaustion.[55] In other words, though it is possible for fatigue to result in performance changes, it can also manifest as altered neuromuscular activity that allows us to maintain a task at the same intensity without necessarily sacrificing performance.

Muscle fatigue changes both movement kinematics[56] and the ability of muscles to act as dynamic joint stabilizers.[57] Fatigue of the shoulder girdle has been proposed as a mediator between muscle imbalances, repetitive movements, and shoulder injury.[58-60] Periscapular muscles, notably the trapezius and serratus anterior, are responsible for scapulothoracic stability, and fatigue in these muscles can influence scapular kinematics and positioning, creating greater risk of subacromial impingement.[56, 61] Similarly, stability of the humeral head within the glenoid fossa relies on the compression provided by the rotator cuff muscles to counteract the translational forces exerted by pectoralis major, latissimus dorsi, and deltoid.[62] Indeed, fatigue-induced abnormal kinematics of the rotator cuff has been connected to superior humeral migration[63] as well as anterior tilt of the scapula.[64] Finally, proprioception, which could be important for correctly replicating healthy movement patterns, is also influenced by fatigue. Exercise-induced muscular fatigue produces deficits in shoulder proprioceptive acuity which outlasted fatigue-related strength impairments: even when muscle strength had recovered to pre-fatigue levels, joint position sense was still affected.[65]

Fatigue in the sport context is often connected to practicing the same movements or using the same muscles repeatedly. Dale et al.[66] observed that male collegiate baseball players who performed repetitive maximal baseball pitches experienced fatigue in both internal and external rotators of the shoulder, with the internal rotators in the eccentric direction displaying the most fatigue.[66] Despite this, the pitchers maintained ball velocity.[66] In a study in which swimmers performed 8x100m swims and displayed markers of metabolic fatigue, stroke length and range of motion of both arms was reduced, as was joint position sense of their dominant arm.[57] Similar to the baseball pitchers who maintained throw speed, the swimmers' performance, i.e. swim time, did not change.[57] Adapting their muscle activation and coordination strategies could be one way high-level athletes maintain task performance despite fatigue – even if it means inadvertently putting joints in more vulnerable positions.

Electromyographical Changes with Fatigue

Although there are peripheral factors that influence surface EMG amplitude,[67, 68] in low-force fatiguing contractions, EMG amplitude has been shown to increase,[69] possibly due to increased motor unit recruitment, firing frequency and/or synchronization of motor unit recruitment.[52, 70, 71] During repetitive maximal dynamic contractions, EMG RMS is less consistent, with some individuals showing increased RMS when fatigued and other demonstrating decreased RMS, largely depending on the mechanical role of the given muscle towards producing the task.[68, 72] After male swimmers performed a 3-minute all-out on-land task that simulated the pull phase of swimming, researchers reported a fatigue-associated decrease in serratus anterior RMS during arm elevation with increased lower trapezius muscle activity as a compensatory strategy to control the increase in anterior tilt of the scapula.[56] When examining the EMG power spectrum, a decrease in mean or median frequency is relatively consistent in reflecting biomechanical fatigue (i.e. reductions in the maximal force-production capacity) and occurs in large part due to decreases in muscle fibre conduction velocity.[48, 71, 72] Functional connectivity has been introduced in the scientific literature more recently. Similarly to the literature on the effects of fatigue on coactivation, some studies suggest that an increase in functional connectivity occurs with fatigue to promote joint stabilization,[73] although others have observed a decrease following a repetitive task, which could again be due to the varying mechanical roles played by each muscle towards task production.[74]

Sex Differences in Electromyographical Fatigue Responses

The literature on electromyographic sex differences in sport-related upper limb fatiguing tasks is lacking. Current knowledge of sex-specific shoulder muscle activity stems primarily from the body of literature investigating simulated work-related tasks: another area where repetitive tasks, and the ensuing fatigue, causes conditions favourable for injury,[75] with females reporting more neck and shoulder injuries than males.[20] When completing different repetitive tasks with identical performance outcomes, males and females have been shown to demonstrate differences in their joint contributions,[76] muscle activity,[77, 78] and functional connectivity between muscle pairs.[78] When completing a fatiguing repetitive pointing task, despite having similar performance and EMG RMS responses to fatigue in the muscles of the upper limb, sex differences in variability and inter-muscle connectivity – as well as the way these parameters changed with fatigue – indicated differing fatigue management adaptations and strategies.[79, 80]

These results of neuromuscular sex differences in fatigue are derived from repetitive tasks of low-to-medium force. Since sex differences in fatigability vary depending on the task, intensity, and type of contraction,[21, 81] it is difficult to predict if and what kind of sex differences exist for high-intensity, ballistic movements like those performed by water polo athletes. Just as what was done with the lower limb, efforts in comparing shoulder muscle activation, fatigue responses, and functional connectivity between the sexes could elicit shared and sex-specific vulnerabilities that predispose overhead athletes to injury, as well as desirable vs. undesirable fatigue adaptations. Beyond sport, neuromuscular sex differences in both dynamic and high-intensity contractions represent an area where many questions have yet to be answered.

In summary, because of the repetitive demands placed on the shoulder through swimming and throwing, injuries to the shoulder are the most common among water polo players. There remains to be a clear consensus, but current literature suggests that it is possible there are important sex differences in both rate of injury and mechanism of injury. This neuromuscular aspect of movement control may also be one piece of the puzzle as to why females and males exhibit different injury rates and/or movement patterns for similar tasks. To the best of our knowledge, no other study has examined electromyographic sex differences during ballistic upper limb tasks and how they are influenced by fatigue. Therefore, our objective was to compare the main effects of sex and fatigue, as well as their interactions, on neuromuscular parameters of the shoulder muscles and strength-related performance measures among elite water polo players. We hypothesized that during maximal shoulder efforts, females and males would differ in their muscle activations, as well as in their responses to fatigue. We further predicted that females would have higher levels of functional connectivity, and that when lean bodyweight was unaccounted for, males would produce higher torque and ball velocities.

RESEARCH ARTICLE

Sex differences in shoulder muscle activation and fatigue among elite water polo players

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Abstract

Purpose

The shoulder is the most common site of injury among water polo players. Since female athletes have been shown to experience more overuse shoulder injuries, this study aimed to investigate sex differences in neuromuscular parameters of the shoulder musculature, maximal torque production, and throwing velocity before and after fatigue.

Methods

Eleven female (21.45 ± 5.82 years, 79.95 ± 14.75 kg) and fifteen male (21.47 ± 2.39 years, 94.21 ± 11.17 kg) elite water polo players performed maximal concentric external and internal shoulder rotations, as well as maximal seated water polo ball throws, before and after an internal shoulder rotation fatiguing task. The shoulder rotations and the fatiguing task were performed using an isokinetic dynamometer. Surface electromyography (EMG) measured muscle activity of pectoralis major, anterior deltoid, posterior deltoid, upper trapezius, and middle trapezius. EMG root-mean-square (RMS) and median power frequency (MdPF) of each muscle, as well as functional connectivity of pairs of adjacent muscles, were used to assess muscle activity and fatigue.

Results

In addition to having mostly similar muscle activation and fatigue responses during maximal internal rotation and seated throwing, when considering lean bodyweight, females and males produced similar internal rotation strength and ball velocities. Middle trapezius RMS and MdPF demonstrated sex-dependent fatigue responses ($p < 0.05$) and males were stronger in external rotation torque even after covarying for lean bodyweight ($p < 0.001$). Functional connectivity among muscle pairs increased after the fatiguing task.

Conclusion

Lean bodyweight accounts for sex differences in internal rotation strength and throwing velocity, but not in external rotation strength – possibly because of sex-specific activation of middle trapezius. After a repetitive fatiguing task, pairs of neighbouring shoulder muscles of both females and males may increase their functional connectivity to work together to improve performance.

1. Introduction

Water polo, a dynamic, high-intensity sport, combines both repetitive, forceful throwing and large volumes of swimming – upwards of 1000m per game.[2, 3] In contrast to land overhead sports like baseball, water polo players lack a solid base of support during throwing, increasing the demand on the shoulder joint.[27] Furthermore, in order to keep their heads out of the water, athletes are forced to use shorter strokes with high elbows, putting the shoulder into increased abduction and internal rotation, increasing early fatigue of the rotator cuff, and potentially compromising joint positioning.[27] Unsurprisingly, the shoulder is the most common site of injury among water polo players,[4] most often the result of overuse due to the combined effects of throwing, swimming, and overhead defending.[5, 6] While the existing literature on sex differences in water polo shoulder injuries remains inconclusive,[4, 10] results from swimming suggest that females have a higher incidence of overuse shoulder injury.[7] In addition, findings in handball – a sport with considerable throwing volume – point to higher rates of shoulder problems in female adolescent[8] and elite[9] players, although the mechanisms underlying these sex differences in injury remain unclear.[20]

Males consistently generate faster ball velocities in throwing movements,[17-19, 38, 39] with some researchers attributing this sex difference to men having higher levels of fat-free mass.[39] Others have found sex-specific throw patterns,[17, 18, 37] including a study reporting multiple differences in joint angles and movement timing among male and female water polo players performing a penalty throw.[37] Most of the literature has focused on kinematic comparisons of throwing between sexes,[17-19, 37] but investigating the neuromuscular aspect of movement control, e.g. the activation and coordination of muscles, may help explain why females and males exhibit different injury rates and/or movement patterns when performing the same task. Indeed, in lower limb movements like soccer kicks,[11] countermovement jumps,[12, 13] jump landings,[12, 14] and cutting maneuvers,[14, 15] females and males have demonstrated different muscle activation patterns, some of which have helped to explain the higher female risk of non-contact ACL injuries.[82] There has been, however, much less substantive research on whether there are similar sex-specific phenomena in mechanisms of sport-related upper limb injury. In studying karate punches, Ferreira & Vencesbrito[83] found that males and females differed in the timing of the activation of some agonist-antagonist muscle pairs, leading them to suggest there were sex differences in neuromuscular coordination. Overall, however, there is a lack of studies that use electromyography to investigate sex differences during unrestricted explosive or maximal movements of the upper extremity.

Athletes are often able to maintain performance despite muscular fatigue, a term which describes the temporary loss of maximal power output[48] and accompanying increase in perceived effort.[49] Dale et al.[66] observed that male collegiate players who experienced internal and external rotation fatigue after repetitive pitching were still able to sustain ball velocity.[66] In a study by Matthews et al.,[57] swimmers performed 8x100m swims and displayed markers of metabolic fatigue. Though stroke length, shoulder range of motion, and joint positions sense were altered, swimmers' performance, i.e. swim time, did not change. Altering muscle activation and coordination strategies could be one way of maintaining task performance despite fatigue, but these adaptations may promote future injury.

Research examining sex differences in neuromuscular characteristics associated to fatigue of the upper limb has focused mainly on work-related tasks. When completing different repetitive tasks with identical performance outcomes, males and females have demonstrated different joint contributions[76] and muscle activity,[77, 78] and females were shown to have greater functional connectivity between muscle pairs.[78, 84] These were all low-intensity, controlled movements, though, and since neuromuscular strategies vary depending on the task, intensity, and type of contraction, it is difficult to predict if, and what kind of, sex differences exist for high-intensity, fatiguing, ballistic movements like those performed by water polo athletes.

Therefore, our objective was to assess the sex-specific effects of fatigue on performance and neuromuscular parameters of the shoulder muscles during throwing and shoulder rotation tasks performed by elite water polo players. We hypothesized that females and males would differ in their muscle activations; that during maximal shoulder efforts, males would produce higher torque and ball velocities, and that this would be associated to their having more lean bodyweight; and that females would have higher levels of functional connectivity. We also predicted that the effects of fatigue on these parameters would differ by sex.

2. Methods

2.1 Participants

The participants in this study represented a convenience sample of 15 elite male Canadian water polo players. Their data, collected during the present study, were used to make comparisons with those obtained in 2017-2018 from 11 elite female Canadian water polo players.[85] All athletes were highly trained at the time of testing (>15h of training per week). Athletes were included if they were between 15-35 years old and if they did not have any injury to the neck or shoulder that resulted in more than one missed practice in the previous six months, any major neck or shoulder surgery, or any cardiovascular impairments. All male athletes were right-hand dominant. Lean body mass values were obtained from athlete anthropometric files, calculated using skinfold measurements. The study was approved by the Research Ethics Board of the Center for Interdisciplinary Research in Rehabilitation, and all participants provided informed consent before beginning the protocol.

2.2 Study Design

Participant height and weight were measured using a physician scale with height rod. Neck and shoulder injury history, and playing experience were also recorded. Each participant performed maximal effort contractions using the isokinetic dynamometer, as well as maximal seated ball throws, before and after an internal rotation fatiguing task (**Fig. 1.**).

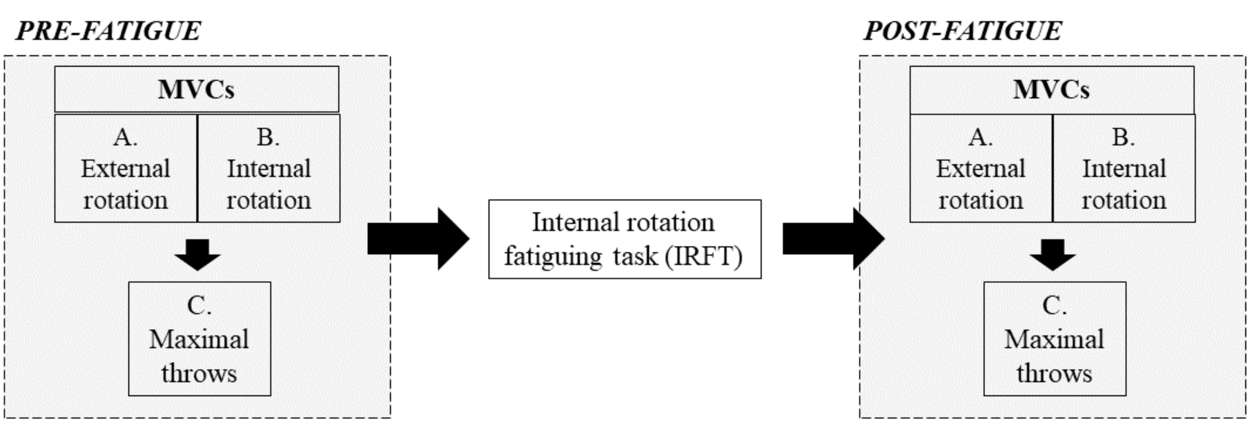

Fig. 1. Study protocol sequence.

2.3 Isokinetic Dynamometer Set-Up and Familiarization

All tasks performed using the isokinetic dynamometer (CON-TREX® MJ, PHYSIOMED ELEKTROMEDIZIN AG, Schnaitach, Germany) were completed in a prone position[86] with the dominant shoulder and elbow abducted and flexed, respectively, at 90°, and at a sampling rate of 256 Hz. The head of the dynamometer motor was positioned such that the motor, the elbow, and the glenohumeral joint were horizontally aligned (**Fig. 2.**). The true internal/external range of motion varied slightly based on individual shoulder flexibility (mean ± SD = 83.2 ± 3.5° for the men, 77.8 ± 5.4° for the women). All rotations throughout the various stages of the protocol occurred at 120°/s, which is within the range of 60-180°/s used in isokinetic torque studies involving swimmers.[87-89] The participant was familiarized to the speed of the dynamometer, as well as the sensation of concentrically contracting within the dynamometer arm attachment, both before and after electrode placement. All measures were gravity-corrected.

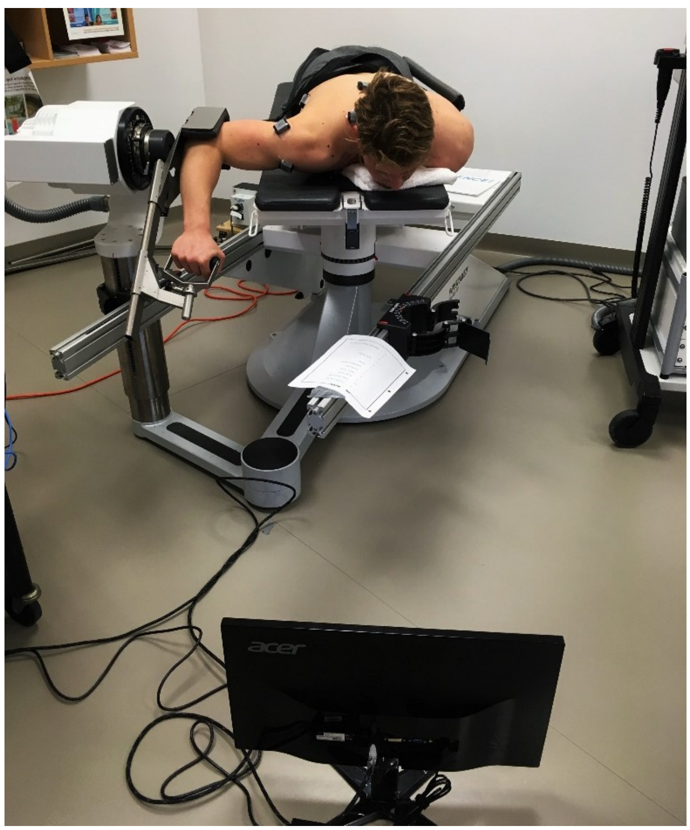

Fig. 2. Position in which participants completed maximal external and internal rotations, as well as the internal rotation fatiguing task (IRFT). The dominant shoulder and elbow were abducted and flexed, respectively, at 90°, and the head of the dynamometer motor was positioned such that the motor, the elbow, and the glenohumeral joint were horizontally aligned.

2.4 Electromyography

Wireless surface electrodes (Delsys Trigno™ Avanti Sensor, Natick, MA, USA; common-mode rejection ratio: 80 dB) were placed on the pectoralis major (PEC), anterior deltoid (AD), posterior deltoid (PD), upper trapezius (UT), and middle trapezius (MT), according to SENIAM recommendations[90] and those established by Barbero et al.[91] (**Table 1**). Data was sampled at 2000 Hz. Before each placement, the skin was shaved and cleaned with alcohol. An additional surface electrode with on-board inertial measurement unit (IMU) was placed on the anterior forearm one finger-width proximal from the wrist to measure the acceleration of the wrist.

Table 1. Surface electrode placements.

Muscle	Placement
Pectoralis major	Around 75% of the line between the acromial angle and the xiphoid process
Anterior deltoid	One finger width distal and anterior to the acromion
Posterior deltoid	Two finger widths behind the angle of the acromion, on the line between the acromion and the little finger
Upper trapezius	Halfway on the line from the acromion to the spine of C7
Middle trapezius	Halfway between the medial border of the scapula and the spine of T3

2.5 Protocol

2.5.1. Maximum Voluntary Contractions (MVCs)

Two sets of three consecutive maximal concentric external rotations were performed, with 60 seconds between each set. The participant was instructed to exert effort solely in external rotation, relaxing completely as the dynamometer passively internally rotated their arm between MVCs. Maximal internal rotation torque was determined in an identical manner: two sets of three maximal concentric internal rotations were performed with passive external rotation in between. Strong verbal encouragement was given to each participant for all MVCs.

2.5.2. Seated Throws

Throws were performed on a swivelling stool 5m away from a makeshift goal net. The participant was permitted to rotate their trunk and upper body, provided their feet remained on the floor pointing towards the net. The participant was instructed to remain still, holding the ball in their lap until indicated to throw the ball, and to pause in their position of release. These two points of no movement served to define the beginning and end of the throw. After five practice throws, five maximal effort throws were completed. Ball velocity was measured using a radar gun (Stalker Pro II, Stalker Radar, Richardson, TX, USA) positioned at shoulder height behind the participant. A mean ball velocity was calculated across the five trials for each participant.

2.5.3. Internal Rotation Fatiguing Task (IRFT)

After the pre-fatigue throws, the participant performed an internal rotation fatiguing task (IRFT) using the isokinetic dynamometer, involving repetitive concentric internal rotation and passive external rotation. Using live visual feedback, each participant was required to maintain an internal rotation torque output of 50 +/- 7.5% of their individual maximal internal rotation torque. At the end of every minute during the task, the participant was asked for a rating of perceived effort (RPE) of their shoulder muscles using a Borg CR10 Scale.[92] After completing a minimum of four minutes, the task was terminated as soon as the participant reported an RPE of 8/10 or greater, or if the torque output was outside the target bandwidth for eight or more repetitions. The participant had no prior knowledge of these termination criteria.

Immediately after the IRFT was terminated, the participant repeated the two sets of three concentric MVCs in external rotation and internal rotation without rest between trials, in order to minimize recovery. These post-fatigue MVCs were followed by five maximal post-fatigue seated throws performed with the same technique as outlined above.

2.6. Data Processing

Pre-fatigue and post-fatigue peak torque corresponded to the single highest value of the MVCs performed in each direction. EMG data for the MVCs and the throws were filtered using a Butterworth 2nd order zero-lag bandpass filter at 20-450Hz and 40-450Hz, respectively.[93] Signals for each muscle were full-wave rectified and normalized to their corresponding pre-fatigue MVC peak. The EMG data for the single MVC that produced the highest torque output in each of the pre-fatigue and post-fatigue MVCs was used for analysis. The plateaus in the visualization of the net acceleration, calculated using the wrist accelerometer data, were identified as the start and end points of the throws. Throw trials were excluded if notable artifacts remained in the signal after filtering.

Using a 100ms moving window, EMG root mean square (RMS) values were calculated for the pre-fatigue MVC, the post-fatigue MVC, and for each of the five pre- and post-fatigue throws. An average EMG RMS was determined for the five pre-fatigue and five post-fatigue throws. Median power frequency (MdPF) was obtained through fast Fourier transform (FFT) for the pre- and post-fatigue MVCs.

Functional connectivity, calculated as the normalized mutual information (NMI) between muscle pairs, was also calculated for the pre-fatigue MVC and the post-fatigue MVC (see Appendix 1. for calculations). NMI was calculated for three pairs of adjacent muscles: AD-PD, AD-PEC, and MT-UT, with one mean value taken to represent each of the pre- and post-fatigue conditions. All data processing was performed using MATLAB and Statistics Toolbox Release 2018b (The MathWorks, Inc., Natick, MA, USA).

2.7. Statistical Analyses

Generalized estimating equations (GEEs) were used to analyze external and internal rotation peak torque, average throw velocity, and EMG measures. The models created for peak torque and average throw velocity included sex (male, female) as a between-subjects factor, and condition (pre-fatigue, post-fatigue) as a within-subjects factor. In order to shed more light onto possible explanatory factors for sex differences, these models were run both with and without lean body mass as a covariate.

To analyze EMG measures during the MVCs and the seated throws, four models were created: (a) mean RMS during the throws, (b) mean RMS during MVCs, (c) MdPF during MVCs, and (d) NMI during MVCs. Sex was included as a between-subjects factor, and condition and muscle (or muscle pair for the NMI model) were the within-subject factors. Wald $\chi 2$ statistics were used to determine the main effects of sex, condition, and muscle (or muscle pair), and their interactions. Pairwise post-hoc comparisons of estimated marginal means, with sequential Bonferroni adjustments, were conducted when there were interaction effects. IBM SPSS Statistics for Windows, version 24 (IBM Corp., Armonk, NY, USA) was used for statistical analyses.

3. Results

3.1. Participants

Data from a total 15 male and 11 female elite water polo players were analyzed for this study. The males were significantly taller, heavier, and had more lean body weight (**Table 2**). All participants reached an RPE of 8 or higher on the Borg CR10 scale during the IRFT.

Table 2
Anthropometric characteristics and playing position of participants.

	Men	**Women**
Age[a]	21.47 ± 2.39	21.45 ± 5.82
Height (cm)[a]*	189.14 ± 6.76	171.49 ± 6.90
Mass (kg)[a]*	94.21 ± 11.17	79.95 ± 14.75
Lean body mass (kg)[a]*	82.00 ± 8.20	63.33 ± 6.51
Position		
Goalie	2	1
Hole set	6	3
Driver/defender	7	6

[a] Data presented as mean ± SD.
* indicates significant difference between sexes ($p < 0.05$).

3.2. Torque and Ball Velocity Measures

For external rotation MVCs, there was a significant Sex × Condition interaction on external rotation torque ($X_1^2 = 10.38, p = 0.001$), as well as a main effect of sex ($X_1^2 = 54.16, p < 0.001$), both of which remained significant when covarying for lean bodyweight ($X_1^2 = 10.90, p = 0.001$ and $X_1^2 = 7.01, p = 0.008$, respectively). Only men experienced a post-fatigue decline in external rotation strength, though they produced significantly more torque than the women regardless of condition (**Table 3**).

In the internal rotation MVCs, before covarying for lean bodyweight, there were significant main effects for both sex ($X_1^2 = 28.97, p < 0.001$) and condition ($X_1^2 = 8.34, p = 0.004$). Men were stronger than women in internal rotation before and after fatigue (mean difference $\pm$ *SE*: 22.76 ± 4.57 Nm and 22.11 ± 3.94 Nm) and declines in torque post-fatigue occurred among both men and women. When including lean bodyweight in the model, the significance of condition as a main effect remained intact ($X_1^2 = 7.00, p = 0.008$), but there was no longer a significant main effect of sex ($X_1^2 = 0.32, p = 0.574$) (**Table 3**).

There was a significant main effect of sex on average ball velocity ($X_1^2 = 44.51, p < 0.001$), indicating greater velocities generated by males than females regardless of fatigue (mean difference $\pm$ *SE*: 2.69 ± 0.43 m/s and 2.80 ± 0.42 m/s). This sex difference disappeared when covarying for lean bodyweight ($X_1^2 = 2.66, p = 0.103$) (**Table 3**). There was also a main effect of condition that was significant without and with lean bodyweight as a covariate ($X_1^2 = 6.12, p = 0.013$ and $X_1^2 = 4.54, p = 0.033$, respectively) as evidenced by lower ball velocities post-fatigue (**Table 3**).

Table 3
Estimated marginal means of maximal torque production and throw velocity pre- and post-fatigue, without (1) and with (2) lean bodyweight as a covariate.

		Pre-fatigue		Post-fatigue	
		Men	Women	Men	Women
(1)	**External rotation (Nm)** $*^c$ $*^s$ †	49.07 ± 1.37	30.04 ± 1.89	44.10 ± 1.46	29.42 ± 1.72
(2)	**External rotation (Nm)** $*^s$ †	46.83 ± 1.26	36.16 ± 2.59	41.86 ± 1.51	34.67 ± 2.55
(1)	**Internal rotation (Nm)** $*^c$ $*^s$	53.25 ± 3.70	30.49 ± 2.69	50.27 ± 3.32	28.17 ± 2.13
(2)	**Internal rotation (Nm)** $*^c$	46.73 ± 2.34	43.17 ± 4.70	43.75 ± 2.85	40.65 ± 4.59
(1)	**Mean ball velocity (m/s)** $*^c$ $*^s$	15.46 ± 0.34	12.76 ± 0.26	15.28 ± 0.33	12.47 ± 0.25
(2)	**Mean ball velocity (m/s)** $*^c$	14.83 ± 0.35	13.83 ± 0.38	14.66 ± 0.39	13.60 ± 0.36

Values presented as mean ± *SE*.
$*^s$ indicates significant main effect of sex ($p < 0.05$). $*^c$ indicates significant main effect of condition ($p < 0.05$). † indicates significant Sex × Condition interaction ($p < 0.05$).

3.3. EMG Measurements

3.3.1. Sex-specific responses to fatigue

There was a significant Sex × Condition × Muscle interaction ($X_4^2 = 21.83, p < 0.001$) for PEC EMG RMS during external rotation MVCs (**Fig. 3A.**). Females had significantly higher PEC RMS than males post-fatigue (13.08 ± 3.14 vs. 6.26 ± 1.19, $p = 0.042$), with a trend to have higher PEC RMS pre-fatigue, as well (13.63 ± 2.87 vs. 7.80 ± 1.01, $p = 0.055$). Females also displayed a significant decrease in AD RMS (38.84 ± 3.53 to 26.22 ± 3.10, $p < 0.001$). Males experienced a significant decrease in MT RMS post-fatigue (58.64 ± 2.19 to 38.24 ± 4.79, $p < 0.001$), such that in the post-fatigue external rotation MVCs, they had significantly lower MT RMS than females (38.24 ± 4.79 vs. 52.65 ± 3.14, $p = 0.012$).

3.3.2. Sex differences independent of fatigue state

In internal rotation MVCs, there was a significant Sex × Muscle interaction ($X_4^2 = 11.98, p = 0.018$) for MdPF: compared to females, males displayed higher MdPF in both PEC (76.60 ± 5.55 Hz vs. 53.73 ± 3.91 Hz, $p = 0.001$) and MT (71.28 ± 3.11 Hz vs. 60.96 ± 2.48 Hz, $p = 0.010$) (**Fig. 4B.**).

3.3.3. Changes with fatigue independent of sex

A significant Condition × Muscle interaction for EMG RMS during external rotation MVCs ($X_4^2 = 31.97, p < 0.001$) revealed similar decreases between the sexes in PD RMS (47.76 ± 2.14 to 32.51 ± 2.60, $p < 0.001$) and UT RMS (53.07 ± 1.56 to 38.58 ± 2.10, $p < 0.001$) (**Fig. 3A.**). There was a significant Condition × Muscle interaction for MdPF in external rotation MVCs ($X_4^2 = 10.43, p = 0.034$), with AD MdPF decreasing (mean $\pm$ *SE*: 80.37 ± 4.40 Hz to 73.23 ± 4.50 Hz, $, p = 0.036$) and MT MdPF increasing (80.13 ± 2.96 Hz to 84.72 ± 3.76 Hz, $p = 0.041$) after fatigue (**Fig. 4A.**).

In internal rotation MVCs, there was a main effect of condition for EMG RMS ($X_1^2 = 12.35, p < 0.001$), with muscles displaying a decrease in EMG RMS (**Fig. 3B.**). A significant Condition × Muscle interaction ($X_4^2 = 12.44, p = 0.014$) revealed that PD MdPF displayed a decrease (77.32 ± 4.56 Hz to 66.88 ± 3.73 Hz, $p = 0.001$) in the internal rotations performed after fatigue (**Fig. 4B.**). The post-fatigue change in functional connectivity during internal rotation MVCs was also similar between the sexes. A main effect of condition ($X_1^2 = 10.468, p = 0.001$) was found, indicating that NMI increased following the IRFT (**Fig. 4B.**).

Finally, there was main effect of condition for EMG RMS during the maximal throws ($X_1^2 = 6.26, p = 0.012$), with muscles producing lower EMG RMS values after fatigue (**Fig. 3C**.).

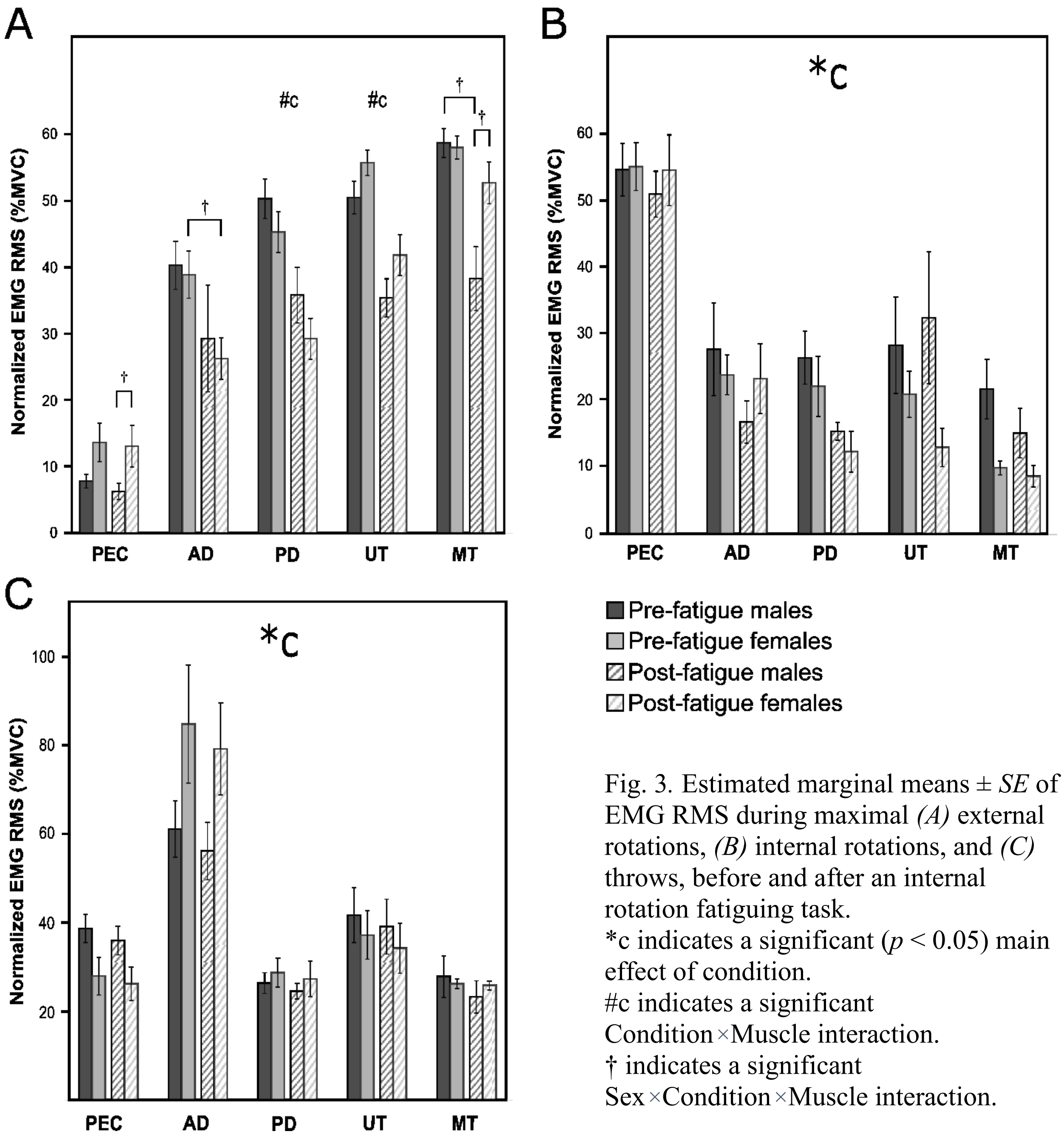

Fig. 3. Estimated marginal means ± *SE* of EMG RMS during maximal *(A)* external rotations, *(B)* internal rotations, and *(C)* throws, before and after an internal rotation fatiguing task.
*c indicates a significant ($p < 0.05$) main effect of condition.
#c indicates a significant Condition × Muscle interaction.
† indicates a significant Sex × Condition × Muscle interaction.

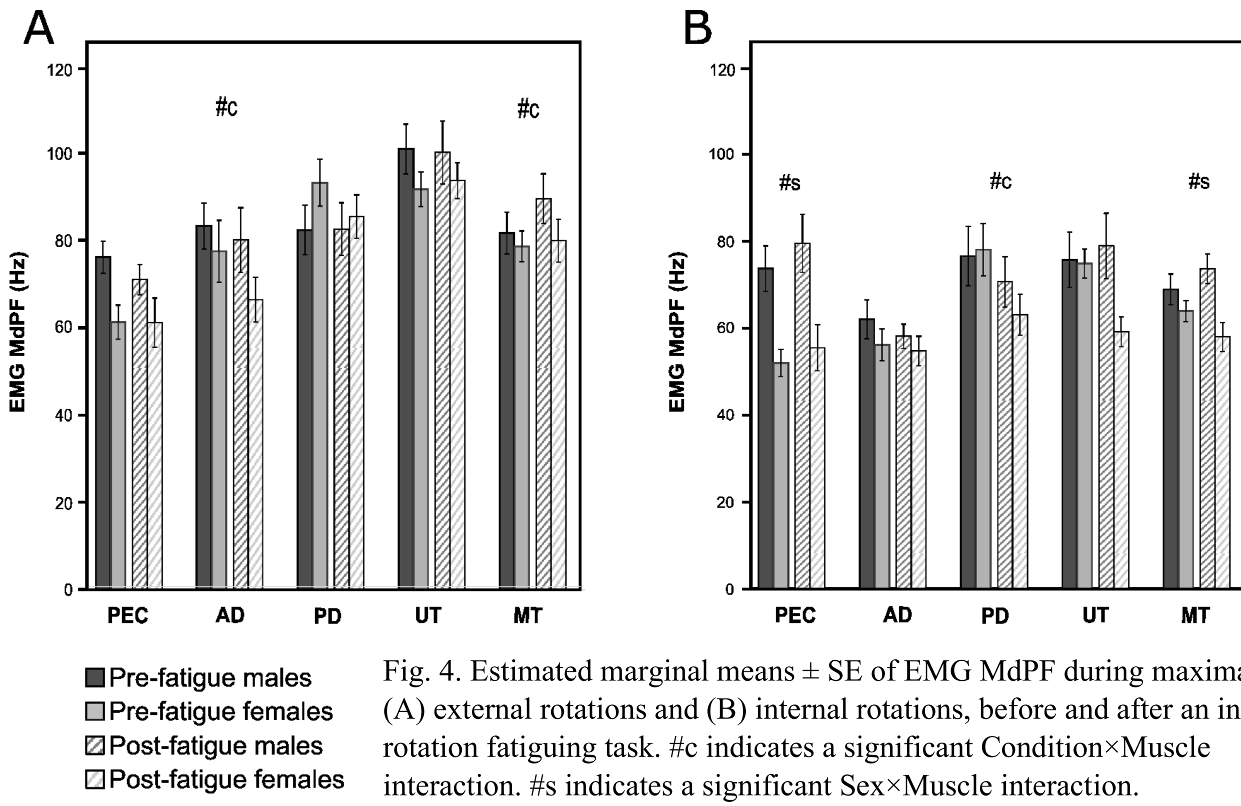

Fig. 4. Estimated marginal means ± SE of EMG MdPF during maximal (A) external rotations and (B) internal rotations, before and after an internal rotation fatiguing task. #c indicates a significant Condition×Muscle interaction. #s indicates a significant Sex×Muscle interaction.

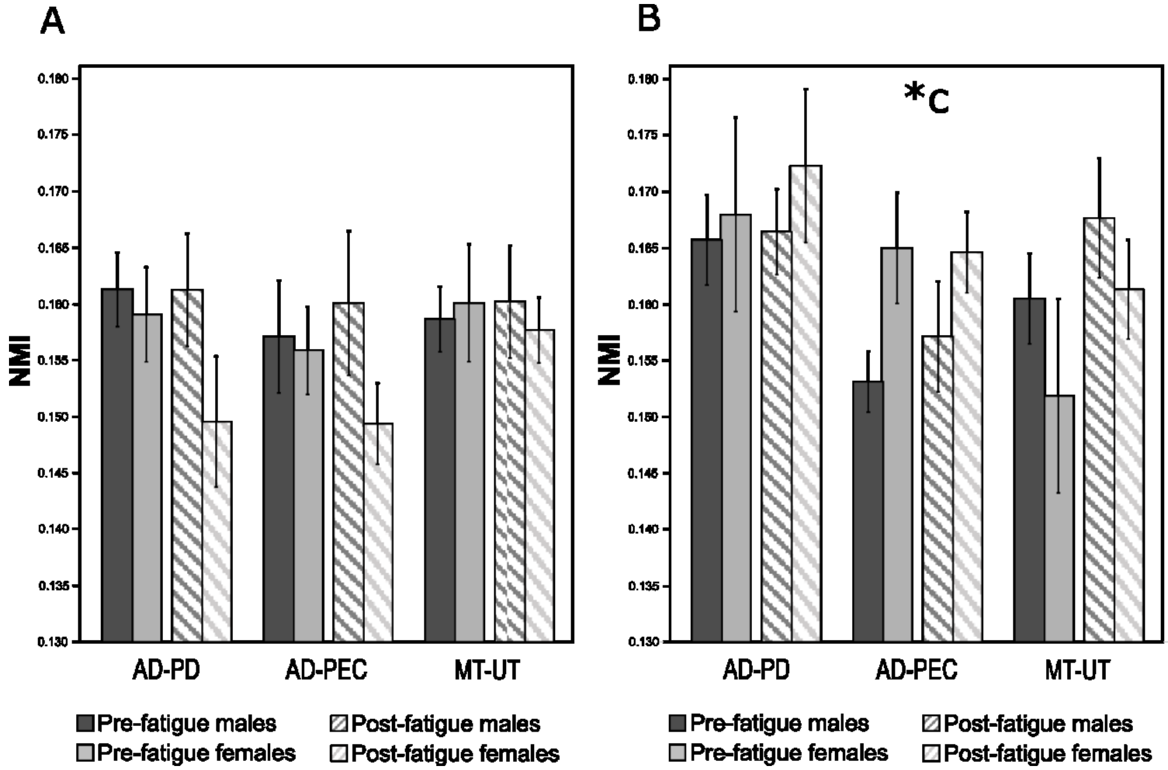

Fig. 5. Estimated marginal means ± *SE* of EMG NMI during maximal *(A)* external rotations and *(B)* internal rotations, before and after an internal rotation fatiguing task. *c indicates a significant ($p < 0.05$) main effect of condition, with participants demonstrating an increase in NMI in post-fatigue maximal internal rotations.

4. Discussion

This study compared not only performance measures between elite female and male water polo players (i.e. maximum torque production and throwing velocity) but, using surface electromyography (EMG), delved further to investigate neuromuscular sex differences during these tasks. Our main findings revealed that 1) maximal external rotation torque remained significantly different between the sexes even after covarying for lean bodyweight, 2) females and males had similar muscle activation and fatigue responses during maximal internal rotations and throws, 3) after fatigue, females and males had similar increases in functional connectivity during internal rotation, and 4) middle trapezius (MT) stood out as having different electromyographical behaviour between sexes.

4.1. Torque and ball velocity

Consistent with other research comparing experienced male and female athletes,[17, 18, 39] the men in the current study produced greater absolute torque in maximal external rotation and internal rotation, as well as higher ball velocities during throws, than the women. When covarying for lean bodyweight, the sex difference disappeared for maximal internal rotation torque and ball release velocity. Similarly, van den Tillaar & Ettema[39] showed that among skilled handball athletes, expressing isometric upper limb strength and throw velocity relative to fat-free mass removed the sex difference, leading them to conclude that men are capable of producing greater force and throw velocity because they have more fat-free mass. Interestingly, maximal external rotation torque was still significantly different between the sexes after covarying for lean bodyweight, suggesting that there may be other factors to consider, such as sex differences in muscle fibre composition, technique, or muscle coordination.

4.2. Electromyographic parameters

4.2.1. Internal and external rotation EMG RMS and MdPF

The internal rotation fatiguing task (IRFT) successfully induced fatigue: all participants demonstrated a decrease in maximal internal rotation force production, as well as an increase in rating of perceived exertion. Females and males displayed decreased EMG RMS, an indication of decreased muscle activity, in their post-fatigue maximal internal rotations. Though the IRFT was at 50% of each participant's internal rotation MVC, as elite athletes, the participants were able to generate very large torque values, such that 50% of their maximum could be categorized closer to maximal activity than to submaximal activity – as it would be for an untrained participant. The considerable physical exertion we observed during the protocol and the high RPEs suggest that this may indeed have been the case. The drop in EMG RMS after the IRFT may thus have represented the fatigue of type II fibres[94] and/or an inability to sustain initially high firing rates.[52] Generally, median power frequency (MdPF) decreases with fatigue, reflecting a decrease in the conduction velocity the muscle fibre membrane.[95, 96] Though none of the muscles other than PD demonstrated significantly lower MdPF in post-fatigue internal rotations, they may have still experienced fatigue. In fact, a previous analysis of MdPF of the female water polo players, along with female controls and elite swimmers, revealed a decrease in MdPF for all muscles from the start to the end of the IRFT.[97] In the current study, efforts were made to perform the post-fatigue MVCs as quickly as possible after the IRFT, but even so, recovery from the IRFT may have started, and previous studies suggest that MdPF in particular recovers faster than both EMG RMS and MVC strength.[98, 99]

During maximal external rotations, females had greater PEC EMG RMS than men. Similarly, in a study that involved isometric shoulder muscle contractions in various positions, females produced higher activation than males in muscles, including pectoralis major, that were not acting in the direction of the movement; in other words, females had more co-activation of stabilising muscles.[100] In the current study, the higher female activation of PEC could be a strategy to eccentrically protect and stabilise the shoulder joint when forcefully externally rotating. However, it could also have restricted their ability to generate maximal external rotation torque, which could explain why external rotation strength was still significantly different between sexes after covarying for lean bodyweight. The electromyographic parameters of MT were particularly interesting. Only males demonstrated a post-fatigue decrease in MT EMG RMS and the sex-independent increase in MT MdPF seems to be primarily driven by the increase experienced by the males (**Fig. 4B**). One possible explanation may be that males activated their MT to a higher degree than females during internal rotation: males had significantly higher MT MdPF in internal rotation and though not significant, appeared to have higher MT EMG RMS than females in internal rotation, too (**Fig. 3B**). If this propensity for higher MT activation remained consistent for the IRFT, the males may have experienced more MT fatigue than the females. This may have in turn influenced their force-producing capability in external rotation and explain why only males demonstrated decreased MT EMG RMS and a post-fatigue decrease in maximal external rotation torque. The increase in MT MdPF is inconsistent with the hypothesis that males experienced MT fatigue, but scapular kinematics and muscle activity are altered under conditions of shoulder rotation fatigue[101] and the power spectra of muscles is also associated with muscle length.[102, 103] The EMG frequency spectrum shifts towards lower frequencies when a muscle is lengthened;[102, 103] if the males exhibited scapular retraction, e.g. by increased activation of the rhomboids, the consequent shortened position of MT fibres could have resulted in a shift towards higher frequencies. An alternative explanation is simply that median power frequency does not always follow a linear relationship with a muscle's force output, particularly at high contraction intensities.[104]

4.2.2. Functional connectivity

Functional connectivity increased during the maximal internal rotations. AD-PEC and MT-UT consisted of muscles that were agonists and stabilizers, respectively, during the IRFT. Previous studies investigating NMI changes with fatigue have reported both increases[45, 47, 73] and decreases[74, 79] in NMI. In elite judokas performing isometric arm abduction to exhaustion, Kawczyński et al.[73] related greater functional connectivity between muscles to greater co-contraction. In the present study, an increase in NMI could point to a strategy of increasing muscle coordination to continue in their roles – move or stabilize – to maintain performance during the IRFT. In contrast to studies by Fedorowich et al.[79] and Johansen et al.[78], but in accordance to one from Cid et al.[74], there were no sex differences in NMI, though it should be kept in mind that they used protocols involved prolonged low-intensity fatiguing tasks among non-elite populations.

4.2.3. Maximal throw EMG RMS

All muscles had decreased EMG RMS in the post-fatigue throws. Similar to a study involving a fatiguing repetitive pointing task,[80], as well as a study that used fatiguing elbow flexions,[105] there were no sex differences in EMG amplitude changes. It should be noted, however, that the throws in the present study differed in that they were maximal effort movements. As well, key muscles involved in shoulder rotation and throwing, like the subscapularis, teres minor, and infraspinatus were not included, and sex differences in the activation and fatigue of these muscles should not be precluded.

4.3. Limitations

The EMG parameters were normalized to those obtained during maximal internal or external shoulder rotation instead of muscle-specific maximal contractions. This meant that normalized EMG RMS and MdPF values could not be interpreted as a percent of the EMG RMS or MdPF during a given muscle's maximal contraction. However, the normalization technique permitted the comparison of EMG parameters between sexes and before and after fatigue, which were the focuses of the present study. Though efforts were made to standardize the time of day of participation, the females and the males completed the protocol at different periods within their training cycles. Differing levels of muscle soreness or altered muscle metabolism resulting from different training intensities could have ununiformly affected EMG measurements,[45] and these findings may also not be generalizable to less experienced athletes. Finally, EMG RMS and MdPF are force-dependent, and because EMG parameters were recorded from maximal tasks in which participants demonstrated decreased force production, changes occurring following the IRFT cannot be attributed to neuromuscular fatigue alone.[106]

5. Conclusion

This is the first study to compare elite female and male overhead athletes in their neuromuscular activation and fatigue patterns when performing maximal shoulder movements. We found that lean bodyweight accounted for sex differences in internal rotation torque and throwing velocity, which were the same tasks for which females and males had similar muscle activation and fatigue responses: decreased muscle activation and increased functional connectivity post-fatigue. Sex differences in external rotation torque were not explained by lean bodyweight and could be due to sex-specific ways in which females and males used their middle trapezius. These results highlight the ability of electromyography to reveal similarities and differences between males and females that may otherwise go unnoticed by solely comparing performance outcome measures or video analysis. Further research to understand the implications of these neuromuscular sex differences on sex-specific injury risk and prevention is warranted.

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Authors' contributions

LD collected, analyzed, and interpreted the data, and drafted the manuscript. SK participated in designing the study and assisting with data collection. JC supervised designing the study and reviewing and editing the manuscript. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

CONCLUSION

The goal of this thesis was to explore the effects and interactions of sex and fatigue on shoulder muscle activation in a previously unstudied context: among elite athletes performing maximal effort movements. We were also interested in whether lean bodyweight would be able to explain sex differences in performance outcome measures. Surface electromyography was used to record the muscle activity of highly trained female and male water polo players while they performed maximal isokinetic external and internal shoulder rotations, as well as maximal water polo ball throws, before and after an internal rotation fatiguing task. Our results indicated that during internal rotations and throws, females and males shared similar muscle activation and fatigue responses: a decrease in EMG RMS after fatigue and increased functional connectivity between pairs of muscles. Interestingly, it was during these same tasks – maximal internal rotations and throws – that lean bodyweight was able to account for sex differences in torque production and ball velocity, respectively. In contrast, lean bodyweight was unable to explain sex differences in maximal external rotation torque; instead, sex-specific motor strategies, particularly those related to the use of middle trapezius, could have played an important role in external rotation performance. This suggests that there may be a movement-specific component to sex differences in shoulder muscle activation. Overall, these results emphasize the strength of electromyography as a tool to identify similarities and differences between females and males that may otherwise go unnoticed with kinematic or performance outcome-related comparisons. Our findings serve as a starting point for the identification of sex-specific shoulder muscle activation and coordination strategies during unrestricted, maximal movements. Future research should explore the neuromuscular parameters of other shoulder muscles, particularly those of the rotator cuff, that are important in generating throwing velocity and stabilizing the joint during repetitive and/or maximal throwing. By building upon the current research, an expanded knowledge of how females and males have similar and disparate motor habits and fatigue adaptations could ultimately help guide sex-specific injury prevention and rehabilitation interventions.

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APPENDICES

Appendix 1. Normalized mutual information (NMI) calculations

Mutual information is a way of measuring how knowledge of one variable reduces the uncertainty of another.[44] Not limited to just linear dependencies, mutual information also considers nonlinear statistical dependencies between measurements X and Y; this quantification of dynamical coupling between X and Y is a measure of their functional connectivity.[44] In the EMG signal X, the average amount of information contained in X is defined as the entropy H:

$$H(X) = -\sum_i p_x(x_i) \log\big(p_x(x_i)\big) \qquad \text{[Eq. 1]}$$

where $p_x(x)$ is the probability distribution of X and $p_x(x_i)$ is the ith bin of the normalized histogram. Forty bins were used to construct the histogram.[45] Given a measurement x_i from the EMG epoch $X = \{x_i\}$, which represents one muscle, and y_j from the EMG epoch $Y = \{y_j\}$, which represents the second muscle, mutual information between the two is:[44]

$$\text{Mutual information}_{XY} = \sum_{x_i, y_j} p_{XY}(x_i, y_j) \log \frac{p_{XY(x_i, y_j)}}{p_x(x_i) P_Y(y_j)} \qquad \text{[Eq. 2]}$$

where $p_{XY}(x_i, y_j)$ is the joint probability density for EMG signals of the two muscles. Mutual information was calculated over 500ms epochs. In order to make comparisons between different muscle pairs, mutual information was normalized to the minimum H of the EMG signals X and Y:[45]

$$\text{Normalized mutual information}_{XY} = \frac{MI_{XY}}{\min\,(H(X), H(Y))} \qquad \text{[Eq. 3]}$$

Normalized mutual information (NMI) can take on values between 0, which indicates complete functional independence, and 1, which indicates complete functional dependence.

Appendix 2. Consent Form

Consent form

Centre intégré de santé et de services sociaux de Laval
Québec

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

1 - Title of project

Effects of shoulder fatigue on muscular patterns and performance in expert water-polo players, expert swimmers, and controls

2 - Researchers in charge of project

Julie Côté, Ph.D. Associate Professor, Department of Kinesiology and Physical Education, McGill University, (514) 398-4184 ext. 0539, (450) 688-9550, ext. 4813.

Lily Dong, B.Sc., Master's student, Department of Kinesiology and Physical Education, McGill University, (514) 398-4455 ext. 0583.

3 - Introduction

Before agreeing to participate in this project, please take the time to read and carefully consider the following information.

This consent form explains the aim of this study, the procedures, advantages, risks and inconvenience as well as the persons to contact, if necessary.

This consent form may contain words that you do not understand. We invite you to ask any question that you deem useful to the researcher and the others members of the staff assigned to the research project and ask them to explain any word or information which is not clear to you.

4 - Project description and objectives

The objective of this research is to measure how expertise, specifically the expertise in aquatics sports, affects the fatigue response. In this project, 15 male water polo players will be recruited to complete this study and their data will be compared to data previously collected from 15 female water polo players. The long-term objective of this research is to better understand how males and females respond differently to muscular fatigue, which can lead to sex-specific interventions or new guidelines that promote safer training for sports involving repetitive movements.

5 - Nature and duration of participation

The experimental procedure will be performed at the Institut National du Sport (INS) in Montreal's Parc Olympique (4141 Pierre-de Coubertin Ave, Montreal, QC H1V 3N7). We ask that you participate in one experimental session lasting approximately 2 hours and consisting of four phases: a preparation phase, a pre-fatigue phase, an experimental phase and a post-fatigue phase. We will ask you to wear sport shoes. ***Some of the procedures are invasive.*** Three small acupuncture-like needles will be placed in the shoulder to record muscular activation throughout all the phases. The use of these needles could make you feel some light pain. We urge you not to participate in the study if you have a strong fear of needles.

During the preparation phase, your height and weight will be collected. Next, the skin will be shaved and cleaned and surface electrodes will be taped onto the skin over muscles of the neck and arm, and needle electrodes will be placed in three muscles of the shoulder. These serve to measure surface and deep tissue muscle activity. You will then be asked to perform a series of muscle contractions. Lastly, the machine on which the experimental phase will be done will be adjusted to your measurements. The preparation phase should last about 45 minutes.

During the pre-fatigue phase, you will be asked to complete 5 maximal throws with a water polo ball. This phase should take 20 minutes.

During the experimental phase, you will be asked to perform a maximal shoulder movement for three repetitions, followed by sub-maximal repetitions of the same movement. These movements are preformed with the help of a machine, as you lie on your stomach in a horizontal position (Figure 1). You will continue until we tell you to stop. Afterwards you will repeat the three maximal repetitions. You will also be asked to rank your perceived effort every 30 seconds. This phase should last about 30 minutes.

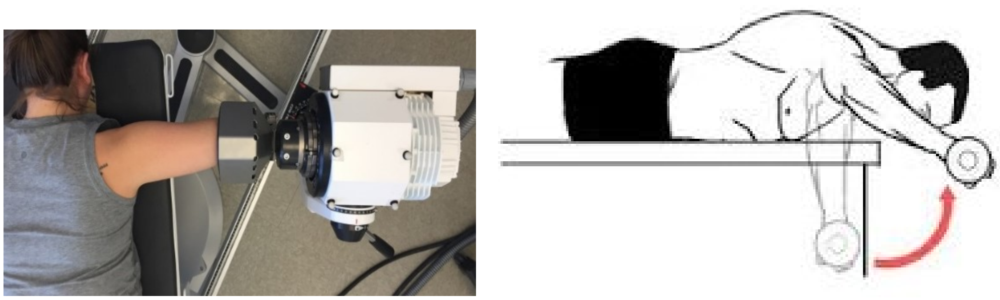

Figure 1 : experimental setup, fatiguing task

During the post-fatigue phase, you will repeat the pre-fatigue task. This phase should last about 15 minutes.

6 - Advantages associated with my participation

As a participant you will receive no direct benefit from your involvement in this study. However, you will contribute to the fundamental science of human physiology and biomechanics and to applied knowledge in sports science.

7 - Personal inconvenience

The duration of the session (approximately 2 hours) may represent an inconvenience for you. The intramuscular EMG needles may also be an inconvenience to you. We are using disposable, single-use needles. If at any point you feel pain or fear from the needles, the protocol will end immediately. The possibility that a few small areas (8, 3x3 cm each) of the skin over your arm and neck may have to be shaved before positioning the electrodes may also represent an inconvenience. The material used respects the usual hygiene norms. Although it is hypo-allergenic, the adhesive tape used to fix the electrodes on your skin may occasionally produce some slight skin irritation. Should this happen, a hypo-allergic lotion will be applied on your skin to relieve skin irritation. You will experience some fatigue towards the end of the sessions, which may cause some arm muscle tenderness or stiffness. If this occurs, symptoms should dissipate within 48 hours following the completion of the protocol.

8 - Confidentiality

All the personal information collected for this study will be codified to insure its confidentiality. Only the people involved in the project will have access to this information. However, for means of control of the research project, your research records could be consulted by a person mandated by the REB of the CRIR establishments or by the ethics unit of the Ministry of health and social services, which adheres to a strict confidentiality policy. All information will be kept under lock and key at the research center of the INS by the person responsible for the study for a period of five years following the end of the study, after which it will be destroyed. If the results of this research project are presented or published, nothing will allow your identification.

9 - Withdrawal of subject from study

Participation in the research project described above is completely voluntary. You have the right to withdraw from the study at any moment. If ever you withdraw from the study, all documents concerning yourself will be destroyed at your request.

10 - Responsibility

By accepting to participate in this study, you do not surrender your rights and do not free the researchers, sponsor or the institutions involved from their legal and professional obligations.

11 - Monetary compensation

A monetary compensation of 30$ will be provided to you at the end of the session for the inconvenience and constraints related to your participation.

12 - Contact persons

If you need to ask questions about the project, signal an adverse effect and/or an incident, you can contact at any time Julie Côté at (514) 398-4184, ext. 0539 or Lily Dong at lily.dong@mail.mcgill.ca..

Also, if you have any questions concerning your rights regarding your participation to this research project, you can contact Ms. Anik Nolet, Research ethics co-ordinator of CRIR at (514) 527-9565 ext. 3795 or by email at anolet.crir@ssss.gouv.qc.ca. The local commissioner for ethics complaints and service quality of the Jewish Rehabilitation Hospital in Laval, Ms Hélène Bousquet, is also available to answer the same questions about your participation in the study. She can be reached at (450-668-1010 ext. 23628 or at plaints@csss.gouv.qc.ca.

ASSENT

I understand that I can withdraw from this study at any time and I understand the implications of my participation to this study. I accept to take part in it.

NAME OF THE MINOR PARTICIPANT: ____________________________

SIGNATURE: ____

SIGNED IN ____________________, on ________________, 20_____.

I, ____________________________, confirm that I explained to the aforementioned child the nature of the research project and the known risks associated to participation in this research and that parent(s) and child have the option of withdrawing from this study at any time. We have confirmed to the child/parents that even if we publish the results of this study, the identity of the child will remain confidential.

Signature of the person in charge
Of the project or their representative: ____________________________

SIGNED IN ____________________, on ________________, 20_____.

CONSENT

I declare to have read and understood the project, the nature and the extent of my participation, as well as risks and inconveniences to which I am exposing myself as described in the present document. I had the opportunity to ask all my questions concerning the different aspects of the study and to receive explanations to my satisfaction. A signed copy of this information and consent form must be given to me.

I, undersigned, voluntarily accept to participate in this study. I can withdraw at any time without any prejudice. I certify that I have received enough time to take my decision.

NAME OF PARTICIPANT (print): ________________________________

SIGNATURE OF PARTICIPANT:________________________________

SIGNED IN _____________________, on _________________, 20_____.

NAME OF THE LEGAL REPRESENTATIVE OF THE INAPT OR MINOR PARTICIPANT: _____________________________

SIGNATURE: ____

SIGNED IN _____________________, on _________________, 20_____.

COMMITMENT OF RESEARCHER

I, undersigned, ________________________________, certify

(a) having explained to the signatory the terms of the present form ;

(b) having answered all questions he/she asked concerning the study ;

(c) having clearly told him/her that he/she is at any moment free to withdraw from the research project described above; and

(d) that I will give him/her a signed and dated copy of the present document.

____
Signature of person in charge of the project or representative

SIGNED IN __________________, on _________________________ 20__.

Appendix 3. Formulaire de consentement

Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Formulaire de consentement

Centre intégré de santé et de services sociaux de Laval Québec

1 - Titre du projet

Effets de la fatigue de l'épaule sur les patrons musculaires et la performance des experts en water-polo, expertes en natation, et contrôles.

2 - Responsables du projet

Julie Côté, Ph.D. professeure agrégée, Département de kinésiologie et d'éducation physique, Université McGill, (514) 398-4184 poste 0539, (450) 688-9550, poste 4813.

Lily Dong, B.Sc., étudiante à la maîtrise, Département de kinésiologie et d'éducation physique, Université McGill, (514) 398-4455 poste 0583, (450) 688-9550, poste 4827.

3 - Préambule

Avant d'accepter de participer à ce projet de recherche, veuillez prendre le temps de comprendre et de considérer attentivement les renseignements qui suivent.

Ce formulaire de consentement vous explique le but de cette étude, les procédures, les avantages, les risques et inconvénients, de même que les personnes avec qui communiquer au besoin.

Le présent formulaire de consentement peut contenir des mots que vous ne comprenez pas. Nous vous invitons à poser toutes les questions que vous jugerez utiles au chercheur et aux autres membres du personnel affecté au projet de recherche et à leur demander de vous expliquer tout mot ou renseignement qui n'est pas clair.

4 - Description du projet et de ses objectifs

L'objectif de cette recherche est de mesurer comment l'expertise, spécifiquement l'expertise en sports aquatiques, affecte la réponse à la fatigue. Dans ce projet, 15 joueurs de water-polo, seront recrutés pour participer à cette étude. Les données seront comparées avec des données recueillies précédemment sur 15 joueuses de water-polo. L'objectif à long terme de cette recherche est de mieux comprendre comment les hommes et les femmes diffèrent dans leurs réponses à la fatigue musculaire, ce qui pourrait mener à l'identification de normes d'entraînement plus sécuritaires pour les sports de mouvements répétitifs.

5 - Nature et durée de la participation

Le protocole de recherche sera effectué à l'Institut National du Sport (INS) du Parc Olympique de Montréal (4141 Pierre-de Coubertin Ave, Montreal, QC H1V 3N7). Nous vous demandons de participer à une séance expérimentale d'environ 2 heures et qui consistera en quatre phases : une phase de préparation, une phase pré-fatigue, une phase expérimentale, et une phase post-fatigue. On vous demandera de porter des souliers de sport. ***Certaines des procédures décrites sont invasives.*** Trois petites aiguilles semblables à des aiguilles d'acuponcture seront insérées dans votre épaule afin d'enregistrer l'activation musculaire durant chaque phase expérimentale. L'utilisation de ces aiguilles pourrait vous faire ressentir une très légère douleur. Nous vous conseillons fortement de ne pas participer à l'étude si vous avez une forte peur des aiguilles.

Durant la phase de préparation, votre poids et votre grandeur seront mesurés. Ensuite, la peau sera rasée et nettoyée et des électrodes de surface seront apposées sur la peau de votre bras et de votre cou et des électrodes aiguilles seront placées dans trois muscles de votre épaule. Elles serviront à mesurer l'activité des muscles de surface et plus profonds. Ensuite, on vous demandera d'effectuer plusieurs efforts avec vos muscles. Finalement, la machine avec laquelle la phase expérimentale sera effectuée sera ajustée à vos mesures. Cette phase durera environ 45 minutes.

Durant la phase pré-fatigue, on vous demandera d'effectuer 5 lancers maximaux d'un ballon de waterpolo. Cette phase durera environ 20 minutes.

Durant la phase expérimentale, on vous demandera d'effectuer une tâche maximale de l'épaule trois fois, suivi de répétitions sous-maximales du même mouvement. Ces mouvements seront effectués à l'aide d'une machine alors que vous serez allongée sur votre ventre dans une position horizontale (Figure 1). Vous allez continuer cette procédure jusqu'à ce qu'on vous dise d'arrêter. Ensuite, vous allez répéter les trois efforts maximaux. Nous vous demanderons aussi d'évaluer votre perception de votre effort chaque 30 secondes. Cette phase durera environ 30 minutes.

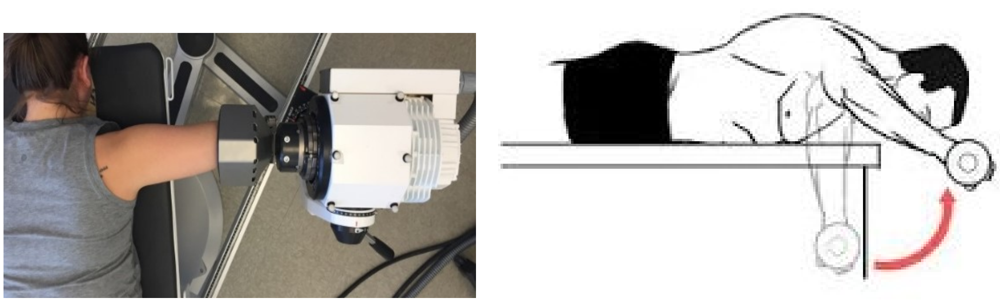

Figure 1 : montage expérimental, tâche de fatigue

Durant la phase post-fatigue, vous allez répéter la tâche effectuée en phase pré-fatigue. Cette phase durera environ 15 minutes.

6 - Avantages pouvant découler de votre participation

En tant que participant, vous ne retirerez personnellement pas d'avantages à participer à cette étude. Toutefois, vous aurez contribué à l'avancement de la science fondamentale de la physiologie humaine et de la biomécanique et aux connaissances appliquées en science du sport.

7 - Inconvénients personnels

La durée de la séance expérimentale (environ 2 heures) peut représenter un inconvénient pour certaines personnes. Les électrodes aiguilles peuvent également représenter un inconvénient pour vous. Nous utilisons des aiguilles jetables à usage unique. Si à un moment vous expérimentez de la douleur ou de la peur des aiguilles, le protocole sera terminé immédiatement. La possibilité que quelques régions (8, 3x3 cm chaque) de la peau de votre cou et de votre bras doivent être rasées avant d'y apposer des électrodes peut également représenter un inconvénient pour vous. Le matériel utilisé respecte les règles d'hygiène usuelles. Toutefois, bien qu'il soit hypo-allergène, le ruban adhésif utilisé pour maintenir les électrodes sur la peau peut occasionnellement provoquer de légères irritations de la peau. Le cas échéant, une lotion hypo-allergène sera appliquée pour soulager l'irritation cutanée. Vous ressentirez de la fatigue vers la fin de la séance expérimentale, ce qui pourrait causer de la sensibilité ou de la raideur des muscles du bras. S'ils se manifestent, les symptômes devraient disparaître dans les 48 heures suivant la fin du protocole expérimental.

8 - Confidentialité

Tous les renseignements personnels recueillis à votre sujet au cours de l'étude seront codifiés afin d'assurer leur confidentialité. Seuls les membres de l'équipe de recherche y auront accès. Cependant, à des fins de contrôle du projet de recherche, votre dossier de recherche pourrait être consulté par une personne mandatée par le CÉR des établissements du CRIR ou de l'Unité de l'éthique du ministère de la Santé et des Services sociaux, qui adhère à une politique de stricte confidentialité. Toutes les données seront conservées sous clé au centre de recherche de l'Hôpital juif de réadaptation par la responsable de l'étude pour une période de 5 ans suivant la fin du projet, après quoi, elles seront détruites. En cas de présentation de résultats de cette recherche ou de publication, rien ne pourra permettre de vous identifier.

9 - Retrait de la participation du sujet

Votre participation au projet de recherche décrit ci-dessus est tout à fait libre et volontaire. Il est entendu que vous pourrez, à tout moment, mettre un terme à votre participation. En cas de retrait de votre part, tous les documents vous concernant seront détruits à votre demande.

10 - Clause de responsabilité

En acceptant de participer à cette étude, vous ne renoncez à aucun de vos droits ni ne libérez les chercheurs, le commanditaire ou les institutions impliquées de leurs obligations légales et professionnelles.

11 - Indemnité compensatoire

Une indemnité compensatoire de 30$ vous sera remise à la fin de la séance en contrepartie des inconvénients et contraintes découlant de votre participation.

12 - Personnes ressources

Si vous désirez poser des questions sur le projet ou signaler des effets secondaires, vous pouvez rejoindre en tout temps Julie Côté au (514) 398-4184 poste 0539 ou Lily Dong au lily.dong@mail.mcgill.ca.

De plus, si vous avez des questions sur vos droits et recours ou sur votre participation à ce projet de recherche, vous pouvez communiquer avec Me Anik Nolet, coordonnatrice à l'éthique de la recherche des établissements du CRIR au (514) 527-9565 poste 3795 ou par courriel à l'adresse suivante: anolet.crir@ssss.gouv.qc.ca. Pour ces mêmes questions, vous pouvez aussi communiquer avec Mme Hélène Bousquet, commissaire locale aux plaintes et à la qualité des services de l'Hôpital juif de réadaptation du CISSS de Laval, au (450) 668-1010 poste 23628 ou au plaintes@csss.gouv.qc.ca.

ASSENTIMENT

Je comprends que je peux mettre fin à ma participation à cette étude en tout temps et je comprends ce qu'implique ma participation à cette étude. J'accepte d'y prendre part.

NOM DU PARTICIPANT MINEUR: _________________________________

SIGNATURE : ____

Fait à ________________, le ___________, 20_____

Je, …………………………………………..confirme que j'ai expliqué à l'enfant mentionné ci-haut la nature de l'étude du projet de recherche et les risques connus impliqués dans la participation à cette recherche et que parent(s) et enfant ont l'option de se retirer de cette étude en tout temps. Nous avons assuré l'enfant/les parents que malgré la publication des résultats de l'étude, l'identité de l'enfant sera tenue confidentielle.

Signature du responsable
du projet ou de son représentant : ________________________________

Fait à ___________________, le _______________ 20____ .

CONSENTEMENT

Je déclare avoir pris connaissance et compris le présent projet, la nature et l'ampleur de ma participation, ainsi que les risques et les inconvénients auxquels je m'expose tel que présenté dans le présent formulaire. J'ai eu l'occasion de poser toutes les questions concernant les différents aspects de l'étude et de recevoir des réponses à mes questions. Une copie signée de ce formulaire d'information et de consentement doit m'être remise.

Je, soussigné(e), accepte volontairement de participer à cette étude. Je peux me retirer en tout temps sans préjudice d'aucune sorte. Je certifie qu'on m'a laissé le temps voulu pour prendre ma décision.

NOM DU PARTICIPANT : ____

SIGNATURE : ____

Fait à ________________, le ___________, 20_____

**NOM DU REPRÉSENTANT
LÉGAL DU PARTICIPANT
INAPTE OU MINEUR : ____**

SIGNATURE : ____

Fait à ________________, le ___________, 20_____

ENGAGEMENT DU CHERCHEUR

Je, soussigné (e), ________________________________ , certifie

(a) avoir expliqué au signataire les termes du présent formulaire;

(b) avoir répondu aux questions qu'il m'a posées à cet égard;

(c) lui avoir clairement indiqué qu'il reste, à tout moment, libre de mettre un terme à sa participation au projet de recherche décrit ci-dessus;

et (d) que je lui remettrai une copie signée et datée du présent formulaire.

____

Signature du responsable du projet
ou de son représentant

Signé à __________________, le ______________ 20__.

Appendix 4. Modified Borg CR10 Scale (English)

RATING	Description
0	Nothing
0.5	Very, very light
1	Very light
2	Light
3	Moderate
4	Somewhat hard
5	Hard
6	
7	Very hard
8	
9	
10	Maximal

Appendix 5. Modified Borg CR10 Scale (French)

RATING	Description
0	Rien du tout
0.5	Très, très faible
1	Très faible
2	Faible
3	Modéré
4	Plutôt fort
5	Fort
6	
7	Très fort
8	
9	
10	Maximal