Sport-specific expertise effects on motor adaptations during a fatiguing repetitive shoulder task

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For my family,

Mom, Dad, Kaitlyn, and Vaughn
and of course, my crazy, Soleil

CONTRIBUTION OF AUTHORS

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ABSTRACT

The aim of this Master's project was to investigate the effects of aquatic sport-specific expertise on neuromuscular patterns of the fatigue response for neck/shoulder muscles. Female participants were recruited into three groups: controls, expert swimmers, and expert water polo players. Participants first completed maximal voluntary shoulder internal rotations, where peak torque output was recorded. Then, they performed a repetitive, concentric internal rotation task at 42.5-57.5 percent of their peak torque. The participant continued until either reporting 8 on the modified Borg C10 scale for shoulder effort or missing the allotted effort bandwidth 8 or more consecutive times. During the task, surface and intramuscular electromyographical (EMG) data and ratings of perceived exertion (RPE) were recorded every minute. Results showed that water polo players reached the fatigue criteria more quickly, although this is likely due to their significantly higher maximum torque output which made for a more difficult fatiguing task. In all groups, there were decreases in median power frequency (MdPF) for all muscles, increases in EMG root mean square (RMS) for the pectoralis major and anterior deltoid, increases in coefficient of variation (CoV) for the anterior deltoid, posterior deltoid, upper trapezius, and latissimus dorsi, and increases in functional connectivity for 23 of the 27 of the muscle pairs analyzed. This suggests that the task was successful in inducing localized muscle fatigue and that pectoralis major and anterior deltoid acted as main agonists with the remaining muscles acting as synergists. Compared to swimmers, controls had initially higher posterior deltoid EMG RMS, lower MdPF for the pectoralis, and higher CoV for the anterior deltoid and upper trapezius. For the second half of the task (ie. as fatigue began to develop) controls had higher pectoralis major RMS, lower MdPF for the pectoralis, and higher functional connectivity involving the pectoralis major. Compared to water polo players, controls displayed initially higher EMG RMS and MdPF for the subscapularis. For the second half of the task, controls had higher posterior deltoid EMG RMS, higher subscapularis EMG RMS, lower subscapularis MdPF, higher CoV for the anterior deltoid, and lower functional connectivity involving the upper trapezius. There were no significant differences in fatigue adaptations for EMG RMS or MdPF between swimmers and water polo players, however, water polo players displayed initially higher CoV for the upper trapezius and higher functional connectivity involving the latissimus dorsi or upper trapezius with fatigue. Results show expertise-specific and time-dependent differences in motor adaptions and strategies of shoulder

internal rotators and scapular stabilizers, although more is needed to understand sport-specific fatigue adaptations.

RÉSUMÉ

L'objectif de ce projet de Maîtrise était de quantifier les effets de l'expertise sportive aquatique sur les patrons neuromusculaires des muscles du cou et des épaules en réponse à la fatigue. Des participantes ont été recrutées pour former trois groupes: contrôles, nageuses expertes et joueuses de water-polo expertes. Pour débuter, les participantes ont effectué des rotations internes maximales volontaires de l'épaule, où le torque était enregistré. Après, elles ont exécuté une tâche répétitive de rotations internes concentriques, variant de 42.75-57.5 pourcent de leur effort maximal. La tâche était conçue pour fatiguer les muscles du cou et des épaules, et devait être effectuée jusqu'à l'atteinte de 8 sur l'échelle modifiée de Borg CR10, ou avoir manqué la zone d'effort 8 fois ou plus de façon consécutive. Pendant la tâche, l'électromyographie (EMG) de surface et intramusculaire et les valeurs de l'effort perçu (RPE) étaient enregistrées chaque minute. Les résultats démontrent que les joueuses de water-polo on atteint les critères de fatigue plus rapidement. Ceci peut être expliqué par leur torque maximal significativement plus élevé, causant une tâche fatigante plus difficile. Chez tous les groupes, il y avait des diminutions de fréquence médiane de puissance (MdPF) pour tous les muscles, des augmentations de l'amplitude EMG (RMS) pour le grand pectoral et le deltoïde antérieure, des augmentations de coefficient de variation (CoV) pour les deltoïdes antérieur et postérieur, le latissimus dorsi, et le trapèze supérieur, et des augmentations de connectivité fonctionnelle pour 23 des 27 paires de muscles analysés. Ceci suggère que la tâche a réussi à induire une fatigue musculaire localisée, que le grand pectoral et le deltoïde antérieur ont agi comme principaux agonistes et que les autres muscles étaient des synergistes. Aussi, les résultats démontrent que les contrôles, comparées aux nageuses, étaient caractérisées par des valeurs EMG RMS initialement plus élevées dans le deltoïde postérieur, la MdPF plus petite au grand pectoral, et le CoV plus élevé aux deltoïde antérieur et trapèze supérieur. Pour la deuxième partie de la tâche (quand la fatigue a commencé à se développer), les contrôles avaient de l'activité EMG RMS plus élevée dans le pectoral majeur, la MdPF plus petite au grand pectoral, et la connectivité fonctionnelle plus élevée dans les paires musculaires impliquant le grand pectoral. Comparées aux joueuses de water-polo, les contrôles étaient caractérisées par l'EMG RMS et la MdPF initialement plus élevées au subscapulaire. Pour la deuxième partie de la tâche, les contrôles ont démontré de l'activité EMG RMS plus élevée pour le deltoïde postérieur, le EMG RMS plus élevé dans le subscapulaire, la MdPF plus petite dans le subscapulaire, le CoV plus élevé dans le deltoïde antérieur, et aussi la connectivité fonctionnelle plus petite dans les paires musculaires impliquant le trapèze supérieur. Il n'y a eu aucune différence significative entre les nageuses et les joueuses de water-polo pour les EMG RMS et le MdPF, toutefois, les joueuses de water-polo ont démontré un CoV initialement plus élevé dans le trapèze supérieur et la connectivité fonctionnelle plus élevée dans les paires musculaires impliquant le trapèze supérieur et le latissimus dorsi avec la fatigue. Les résultats soutiennent les recherches précédentes sur les caractéristiques EMG indiquant une fatigue musculaire localisée. De plus, les résultats à la fois soutiennent et contredisent les recherches précédentes concernant les effets de la compétence et du temps sur les adaptations motrices et les stratégies utilisant les rotateurs internes de l'épaule et les stabilisateurs scapulaires, bien que plus de recherches soient nécessaires pour mieux comprendre les adaptations à la fatigue propres aux spécialités sportives.

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INTRODUCTION

Previous studies have shown that repetitive movements with associated fatigue increase the risk of injury[1]. Water polo and swimming are two overhead sports where repetition, fatigue and a struggle to maintain shoulder stability are inherent to performance. Swimmers are known to train for 10 out of 12 months every year, about 5 days a week, and often with two practices per day, and have been shown to perform around 30,000 shoulder rotations per week[2,3]. On top of swimming thousands of meters each week, water polo athletes pass and shoot over 250 repetitions per week at high velocities, with a resultant torque comparable to that of baseball pitchers[4]. The most prevalent injuries among elite overhead athletes are chronic shoulder injuries, which has been shown to cause injury and interrupt training and/or competition in half of a cohort as reported in a previous study[5]. These injuries are most often caused by muscle imbalances arising from fatiguing muscles, which produce improper scapular and humeral kinematics, which ultimately leads to instability in the shoulder and continuous micro trauma on surrounding soft tissues[6-9].

Muscular fatigue is most universally linked to a decrease in a muscle's capacity to generate power along with an increase in perceived difficulty[10,11]. Specific changes in electromyographic (EMG) measures have been associated with signs of fatigue. Past research has interpreted a decrease in median power frequency and an increase in EMG amplitude as being reflective of muscular fatigue in repetitive, submaximal, dynamic tasks[10,12,13]. Further, motor variability has been highlighted as a beneficial strategy to decrease the risk of injury development in repetitive tasks, with some studies suggesting that the variation occurs to slow development of fatigue, to relieve the load on fatiguing tissues, as well as attempt to preserve performance[14-16]. Another strategy that has been evaluated as a possible injury prevention strategy is inter-muscle functional connectivity, quantified using normalized mutual information (NMI) between two EMG time series. Some studies have suggested that high NMI helps maintain stability and alleviate localized fatigue by sharing the load between neighboring muscles, whereas other suggest that it is not necessarily an advantageous strategy[17-19].

The existing body of literature on the relationship between sport-specific expertise, fatigue, and associated neuromuscular patterns in response to fatigue is limited. Thus, the general objective of this thesis was to measure the effects of aquatic sport-specific expertise on neuromuscular patterns of the fatigue response in sport-specific tasks. The specific objectives were to evaluate the effect of aquatic sport-specific expertise on endurance measures (time-to-fatigue) in a repetitive shoulder task. The second was to quantify the effect of aquatic sport-specific expertise on neuromuscular patterns (amplitude, frequency, variability, and functional connectivity characteristics) in pre-fatigue, median task minute, and post-fatigue conditions of a submaximal, repetitive, prone shoulder internal rotation task.

There were five main hypotheses for this study. First, we hypothesized that both water polo and swimming expert groups would perform the fatiguing task longer before reaching the fatigue criteria compared to the controls, however swimmers would last the longest out of the three groups. Second, we hypothesized that fatigue would be associated with increases in amplitude, motor variability, and mutual information as well as decreases in frequency amongst the various neck/shoulder muscles and muscle pairs. Third, we hypothesized that amplitude would be higher and frequency would be lower in controls compared to both expert groups with swimmers having lower amplitude and higher frequency than water polo players. Fourth, we hypothesized that both expert groups would have higher levels of variability compared to controls, however water polo players would have the highest levels of motor variability. Fifth, we hypothesized that both expert groups would have higher functional connectivity than controls at all time points, however swimmers would have the highest levels of functional connectivity with fatigue. Results from this study will help to better understand the effect of sport-specific expertise on the fatigue response in a submaximal, prone shoulder internal rotation task. Results may also provide more insight into identifying abnormal fatigue adaptation patterns, which could in turn help create rehabilitation interventions to deal with, or even prevent, fatigue-associated injuries in a variety of populations.

LITERATURE REVIEW

Anatomy of the Shoulder Joint

The shoulder/glenohumeral (GH) joint is comprised of the scapula and its glenoid cavity, acromion, and coracoid process, as well as the clavicle and the humeral head. It is a ball-and-socket joint, the least stable but most mobile type of joint in the human body. The joint is stabilized and moved through multiple upper limb tendons and muscles which insert and originate at various locations in the GH joint and surrounding structures. Muscle function is often task-dependent[20]; however, in general, external rotation of the humerus is performed by the infraspinatus (IS), supraspinatus (SS) and teres minor (TM) muscles. The humerus is internally rotated by the anterior deltoid (AD), subscapularis (SUB), pectoralis major (PEC), and latissimus dorsi (LAT). Humerus abduction is performed by the SS, AD, middle deltoid (MD), and posterior deltoid (PD). The upper trapezius (UT), middle trapezius (MT), and lower trapezius (LT) muscles function to stabilize, elevate, and/or depress the scapula. Lastly, the rotator cuff muscles (SS, IS, SUB, TM) also work to stabilize the scapula and ensure fluid movement. The GH joint is the most mobile joint in the body and requires complex and concurrent coordination to ensure functional stability[21]. In movements performed by overhead athletes, the requirements to enhance performance conflict with the requirements to prevent injury. In overhead throwing athletes, in order to reach extreme positions and to create a whip-like movement to impart high velocity on the ball, the athlete's shoulder must be very mobile. However, this counteracts the need for the shoulder to remain stable, which is necessary for the humeral head to stay in a good position within the glenoid socket during rotation and not dislocate out of it. With each throw, large loads are put on the soft tissues. The overall lack of stability and poor joint positioning makes the athlete more susceptible to injury. This is referred to as the "thrower's paradox"[22,23]. This mobility-stability balance is also seen in competitive swimmers, as flexible shoulders are needed to achieve maximum range of motion (ROM).

To prevent injury, athletes strive for an optimal balance between mobility and stability when performing overhead movements[24]. This balance requires muscular strength, muscular endurance, flexibility, and neuromuscular control, without which functional instability will arise[25,26]. This balance is difficult to maintain in repetitive and fatiguing conditions, which are two well-known risk factors for shoulder musculoskeletal disease (MSD) development[1]. The resulting muscle imbalance leads to improper scapular and humeral kinematics, which affect muscle activation timing, the coordination of the movement, force production, as well as decreased performance[6,7]. This overuse due to improper mechanics ultimately leads to continuous micro-trauma to surrounding soft tissues[8,9,14]. Elite athletes are one type of expert population that continuously trains in a repetitive fashion, with high levels of fatigue. On top of this repetition and fatigue, the load on the tissue is often larger in sports environments due to the high forces placed on the shoulder during the overhead movement[27].

Water Polo and Swimming Injury Prevalence and Mechanics

The most prevalent injuries among elite overhead athletes are chronic shoulder injuries. A study conducted by Joshi, Thingpen, Bunn, Karas, & Padua (2011) investigated reports of injury in a population of 372 athletes, ranging from recreational to elite athletes, specialized in badminton, basketball, gymnastics, squash, swimming, table tennis, tennis, or volley ball. Results showed that as many as 44% experienced shoulder problems which caused them to temporarily interrupt training/competition and 29% reported shoulder pain at some point in their careers[5,28]. Water polo and swimming are two overhead sports where repetition, fatigue, high force, and a struggle to maintain the mobility-stability balance are frequently seen. Below, we highlight results of studies investigating injuries in each, as well as movement characteristics that are specific to each sport and that may represent common or distinctive injury risk factors.

Swimming

Swimmers are known to train for 10 out of 12 months every year, about 5 days a week, often with two practices per day[2]. The total distance covered by a competitive swimmer can total around 60,000 – 80,000 meters per week, which equals around 30,000 shoulder rotations per week, and 80% of the training is spent in the overhead, freestyle stroke [2,3,29]. The freestyle stroke is comprised of three parts: the catch phase, the pull through, and the recovery phase. The first part of the stroke, or the catch phase, starts as the forward hand enters the water, and the scapula is elevated by the UT and retracted by the rhomboids. The second part, or the pull through, is defined as the moment where the PEC, AD, LAT, and SUB internally rotate and adduct the GH joint to bring the arm down towards the lower limbs[30]. During the recovery, or final, phase, the MD, PD and SS move the shoulder to an overhead and externally rotated position. Thus, the motion at the

GH joint during the freestyle stroke involves repeated contraction of and coordination between several stabilizing and mobilizing muscles, specifically those generating abduction/adduction and internal/external rotation, to achieve an optimal freestyle stroke[30].

Past studies have found that the propulsive forces needed to swim are mostly produced from the upper limbs, specifically through arm abduction and internal rotation, which may add to muscle imbalances and lead to injury[31,32]. Another factor that may contribute to overuse shoulder injuries in swimmers is excessive training, which leads to fatigue and strain on muscles and continuous stress on surrounding tissues[33]. Swimmers are also known to use equipment such as hand paddles and kick boards, which, if not used properly, can put the arm in an abnormal position and cause reoccurring micro trauma[34]. Studies have reported that up to 66% of elite swimmers have shoulder problems and that between 40-91% have reported pain at some point in their career[29,35]. The intense repetition under fatigue leads to muscle imbalance, scapular diskynesis, laxity, decrease in strength, decrease in ROM, among other issues, which links to a term coined the "swimmer's shoulder", which describes the pain swimmers feel in and about the shoulder temporally related to the act of swimming[33,36,37].

Water Polo

Water polo is a high-intensity sport with increased demands on the shoulder due to both swimming and throwing motions[38]. Shoulder injury has been previously reported to be as high as 80% in elite water polo athletes[39-41]. Water polo athletes pass and shoot over 250 repetitions per week at high velocities (around 50km/h to 80km/h in highly skilled females and males[42,43]), with a resultant shoulder torque comparable to that of baseball pitchers[4]. Similar to the freestyle swim stroke, the throwing motion can be reduced to two movements—abduction/adduction and internal/external rotation - that occur within four phases[44]. The throwing movement begins when the dominant hand lifts the ball[45]. Hip and shoulder rotation initiate the movement of the cocking (first) phase through horizontal abduction as the MD, PD, and SS bring the arm into maximal external rotation, with the elbow and wrist flexed[46]. The UT and serratus anterior protract and rotate the scapula to prepare for the next phase of throwing. In the arm acceleration (second) phase, the trunk and shoulder rotate, while the elbow and hand lag behind. The GH joint internally rotates and adducts horizontally with the help of the SUB, PEC, AD and LAT muscles. The external rotator cuff muscles, including the TM and IS, contract to stabilize the humeral head in the GH joint. The final follow through phase involves a wrist flick to direct the ball at the desired target. Like with the freestyle stroke, repetitive passing and shooting can lead to muscle imbalances, specifically between the dominant and non-dominant shoulders[41]. As well, water polo players have no base of support in the water, thus more of the load is on the shoulder, especially when the athlete is fatigued and unable to propel themselves out of the water[42,47,48].

On top of the throwing repetition, water polo players swim thousands of meters per week and the swimming is often head-up, altering between a sprint and slower pace, or with change of direction[49]. The change in pace, direction, and body position eliminates the usual body roll that a swimmer uses to ensure their arm clears the water during the recovery phase and extends to increase their ROM, which leads the water polo player to use more forced abduction and internal rotation which could lead to earlier fatigue and larger load on the shoulder[39,47]. It is unsure whether injury development in water polo arises mainly from throwing, swimming, or a combination of both[41].

In summary, shoulder fatigue induced by repetition is a known risk factor for shoulder injury mechanisms. Past research has shown that with fatigue, due to the extensive degrees of freedom, the shoulder has the ability to reorganize muscle activity patterns. This ability is considered to be an adaptation strategy which is thought to help combat overload of specific muscles, minimize fatigue, and postpone exhaustion[50]. A detailed understanding of how the shoulder responds to fatigue in repetitive tasks and how the response and strategy differs with relevant expertise may help prevent shoulder injuries.

Electromyography and Fatigue

Muscular fatigue is most universally linked to an exercise-induced response which leads to a decrease in the muscle's maximal capacity to generate force and/or power output, regardless of if task can be sustained[10,11]. Along with this decrease in force or power production is an increase in perceived difficulty to maintain a given target force. Fatigue progresses to exhaustion once there is an inability to produce the target force and sustain the task. There are various methods of measuring and assessing human fatigue. One method frequently used in biomechanics is measuring and analyzing muscle activation with electromyography (EMG), a neuromuscular method that can detect changes in muscle activity. This method involves surface electrodes and/or intramuscular conductive elements which are used to collect the electrical activity of muscles.

Direct quantification of fatigue through EMG is not valid, therefore researchers make inferences based on the physiological responses that accompany fatigue[10,51,52]. The amplitude of the signal reflects the number and size of action potentials directed to the target muscles as contraction signals. Therefore, various parameters of the EMG signal, specifically, the EMG root mean square (RMS), median power frequency (MdPF), EMG coefficient of variation (CoV), and normalized mutual information (NMI) can be calculated and analyzed to infer various neuromuscular phenomena under fatigue.

EMG RMS, MdPF and Fatigue

The EMG root mean square (RMS) is an outcome commonly calculated to reflect the signal's amplitude. It is calculated separately for each muscle and can subsequently be used to analyze the amount of muscle activation at different time points. Moreover, we can determine at which frequencies the muscle activity is concentrated through a power density spectrum analysis. This analysis involves calculating the median or mean power frequency to quantify the changes in spectral content[12]. Researchers can interpret how these parameters are affected by muscular fatigue, as there are common effects elicited by muscular fatigue on EMG amplitude and frequency documented in the literature. One identified effect is an increase in the surface EMG amplitude throughout a submaximal fatiguing task due to an increase in recruited active motor units and firing frequency, however this is observed to occur mainly in sub-maximal, low-force efforts where the motor output is maintained, whereas for high-intensity efforts until exhaustion and ultimately failure, an increase in EMG amplitude is rather observed[10,53-57]. Another effect commonly observed in the presence of fatigue is a decrease in the MdPF, which is related to a decline in muscle fiber conduction velocities[12].

Motor Variability

Motor variability research is emerging in both the ergonomics and sports biomechanics communities[14-16]. The repeatability of EMG measures can also be studied in order to quantify motor variability, a relevant concept especially in repeated movements. The human musculoskeletal system is composed of many joints and degrees of freedom, which allow an individual to perform many variations of a task using a variety of different postures and movements. This repertoire of motor solutions is referred to as motor abundance[58] and the varied use of these solutions over the course of a repetitive task is referred to as motor variability[59]. Motor variability refers to an individual's natural variation in postures, movements, and muscle activity, and can be quantified using kinematic and kinetic variables such as joint angles, velocities, and torques, as well as EMG variables (i.e. muscle activity or recruitment patterns)[15,16]. In EMG data, this variation is typically quantified by calculating the standard deviation (SD) across the RMS data of repeated task cycles and normalizing to the corresponding average RMS to obtain the coefficient of variation[16,17,57].

Motor Variability and Fatigue

In the past, motor variability has been considered as unwanted noise to be reduced or removed, but recent studies now recognize its role in neuromuscular organization[59]. Motor variability has been highlighted as a beneficial strategy to decrease the risk of injury development in repetitive fatiguing tasks[16]. Some studies further claim that a re-organization of motor strategies during a fatiguing task occurs to slow the development of fatigue, relieve the load on fatiguing tissues, as well as attempt to preserve performance[14-16].

Motor adaptations are observed in multiple studies where participants complete a fatigue-inducing repetitive movement. Côté, Mathieu, Levin, & Feldman (2002) evaluated kinematic data from healthy adults aged 23-45 years, completing a repetitive sawing task to fatigue, and found that with fatigue, the subjects maintained performance through a reorganization of joint coordination. The elbow motion amplitude decreased, however there was increased motion amplitude and contribution from non-fatigued joints. Further, kinematic research on a fatigue-inducing overhead hammering found that when fatigued, the healthy participants showed decreased motion and velocity of the elbow joint accompanied by increased trunk movement. This adaption was thought to show compensation for acute fatigue in order to maintain task performance[60]. In addition, Cote, Feldman, Mathieu, & Levin (2008) collected both EMG and kinematic data for the same repetitive hammering task in healthy adults aged 24-46 years and found that there was a decrease in elbow ROM which was thought to help absorb the impact, along with an increase in trunk ROM and external oblique RMS which could be linked to a search for increased momentum and stability. Cycle-to-cycle variability was also seen to increase in a repetitive forward reaching task performed to fatigue[56,57,62]. Fuller, Lomond, Fung, & Côté (2009) found that cycle-to-cycle variability of the shoulder and elbow joint angles increased with fatigue, specifically in the mediolateral direction, in order to maintain proper shoulder and elbow elevation, without a decline in performance. In another study using the same task, with EMG data collected for healthy men and women, higher initial motor variability was linked to greater fatigue endurance in females[57]. An individual's ability to utilize strategies of both motor abundance and motor variability to both resist fatigue and maintain performance may be influenced by personal factors such as age, gender, and experience[16].

Motor Variability and Experience

Experience/expertise in performing specific tasks or movements has also been suggested to influence motor variability. Madeleine, Voigt, & Mathiassen (2008) investigated EMG variability during a simulated meat-cutting task and found that cycle-to-cycle EMG variability was higher in more experienced workers. In the field of human movement, elite athletes are an expert population who continuously train their bodies to cope with the repetitive load required to maintain a high level of performance. Sports science researchers have studied the relationships between performance, fatigue, and motor variability in specific sports tasks. Aune, Ingvaldsen, & Ettema (2008) examined the changes in kinematic coordination in an attacking forehand drive during a table tennis task where the goal was to hit the balls as quickly and accurately onto a circular target and found that with fatigue, both recreational and elite athletes showed increased variability in their stroke characteristics. However, only the elite athletes maintained the same accuracy and speed in their performance with fatigue. In a study investigating the effects of skill in triple jumping on the kinematic coordination variability of the lower extremity, there was higher coordination variability in the most skilled participants[65]. Further, the variabilities of hip and ankle joint variables were found to increase with skill level during race walking[66]. In contrast, Fleisig, Chu, Weber, & Andrews (2009) measured multiple kinematic and kinetic variability parameters and found that variability of the knee and trunk joint angles as well as initial foot placement was greatest for youth pitchers, and was lower in players with higher levels of competition. As well, Button, Macleod, Sanders, & Coleman (2003) determined that while performing a basketball free throw under fatigue, elbow angle variation remained consistent with higher skill levels in order to maintain accuracy. Lastly, Chollet, Delaplace, Pelayo, Tourny, & Sidney (1997) quantified stroke variation characteristics based on stroke rate, length and velocity in men's swimming 100m freestyle race and found that the most skilled athletes kept these characteristics the most constant throughout the race. A possible explanation for these contrasting findings is that variability in experts is a functional variability needed to maintain performance whereas the variability of novices is more closely linked to the subject exploring different motor solutions to accomplish the task[70]. As well, this contrast could depend on how precise the task needs to be. In a situation where an athlete needs to repeat the same task with the exact same outcome, it is possible that they will be less variable in their movement, especially in the movement characteristics that would have the biggest impact on performance such as for instance wrist flexion (as opposed to for example hip flexion) in a free throw shot. High variability would present advantages as long as it would not affect overall performance outcome, a general concept referred to in the motor control literature as "good", vs "bad", variability[71].

In summary, the majority of studies on motor variability suggest that fatigue and experience elicit an increase. This has previously been interpreted as a search for new movement patterns to preserve task performance as fatigue develops and to delay injury[53,60,62]. As well, experience and/or expertise may represent personal factors influencing the ability of the motor system to adjust to fatigue. However, previous studies of variability in experts have mostly investigated kinematic and/or kinetic variability. More studies of this kind, with a focus on EMG variability are required to determine whether there is a relationship between neuromuscular variability, fatigue, and performance.

Normalized Mutual Information

Lastly, the inter-relationships between two or more EMG signals can be studied to infer how different muscles, or muscle sections, coordinate. This is typically done using techniques such as cross-correlation and mutual information. NMI is defined as the amount of "functional or shared connectivity between two muscles[72]." This statistical method uses both linear and non-linear relationships between two EMG time series to quantify co-ordination patterns between muscles[73,74]. Originally used in biomedical research to study coherence between electroencephalographical (EEG) patterns, this technique renders a number between 0 and 1 reflecting the amount of functional connectivity between two signals (0 = no connectivity, 1 = total connectivity). Whereas cross-correlation has been used more often in the literature, NMI is used more recently and is hypothesized to be a more accurate method due to the consideration of non-linearity in signals[75].

NMI and Fatigue

Normalized mutual information has only recently been calculated in association with fatigue and injury risk and has analyzed isometric tasks, dynamics tasks, gender comparisons, and injured vs healthy comparisons. Regarding isometric tasks, Madeleine, Samani, Binderup, & Stensdotter (2011) calculated NMI in a male population who performed repetitive eccentric contractions at 100% MVC to fatigue and found that within-trapezius functional connectivity increased with muscle fatigue and delayed onset muscle soreness. In another study investigating functional connectivity between core and shoulder muscles during isometric contractions in judo athletes, Kawcynski et al. (2015) found that there was an overall increase in NMI with fatigue between all shoulder and core muscle pairs, which was interpreted as a strategy to maintain stability as fatigue developed during the task. In addition, the same study observed that higher NMI between the UT-MT was related to longer task endurance time. In another study by Federowich, Emery, & Côté (2015), functional connectivity was measured during two separate typing tasks – one walking and one sitting. Contradicting results were observed, with higher connectivity in the cervical erector spinae (CES)-AD and the CES-lower trapezius (LT) during the sitting task and lower connectivity in CES-AD pair during walking. The higher connectivity was interpreted as a search to share the load with another muscle in order to continue the task, whereas the lower connectivity was interpreted as a way to isolate fatigue to one muscle to prevent spreading of fatigue symptoms. Regarding dynamic tasks, another study comparing NMI in the forearm during static versus a dynamic task observed lower functional connectivity during the dynamic task[76]. Further, Federowich, Emery, Gervasi, & Côté (2013) measured functional connectivity of upper limb muscles during a repetitive pointing task performed to fatigue, and found that there was an overall decrease in NMI with fatigue. This decrease is thought to be a beneficial strategy due to individuals taking advantage of degrees of freedom compared to an isometric task therefore sharing the load between muscle pairs is less necessary. Regarding gender comparisons, another study measured NMI among trapezius subdivisions during a repetitive, submaximal, box-folding task. There were no changes in NMI with time, however women were observed to have higher trapezius subdivision functional connectivity compared to men.[18] As well, Fedeorowich, Emery, Gervasi, & Côté (2013) found that higher connectivity was seen in females between trapezius subdivisions, where-as initial low NMI in men was considered to be a predictor of higher endurance. Johansen, Samani, Antle, Côté, Madeleine (2013) suggested that the high levels of NMI seen in women suggesting high co-contraction may in fact be a poor strategy and connect to a higher risk of injury. Lastly, two studies measured NMI in injured populations and found that in the presence of sub-acute low-back pain and chronic neck-shoulder pain, there was less functional connectivity, which was explained by a lack of stability with injury and a change in motor control when injured[77,78].

Taken together, recent literature gives contradicting results due to differences in population, task design, etc. Some lean towards suggesting that NMI in not necessarily a beneficial strategy where as others suggest that it is a way to maintain stability and share the load between neighboring muscles. Further, to our knowledge, no studies have investigated the effects of experience and expertise on functional connectivity in a fatiguing task. More studies are needed to understand how muscles work together in response to fatigue and to better understand a personal factor of experience can alter this response.

Summary

The literature on fatigue adaptations during dynamic, repetitive tasks, has increased over the last 2-3 decades, and has recently evolved due to the use of new measurement methods such as variability and mutual information, which provide more insight into how the neuromuscular system deals with the gradual induction of fatigue. Moreover, one particular group of experts, elite aquatics sportsmen and women, may provide insight into beneficial ways to deal with fatigue, especially to contribute to the literature on neck/shoulder fatigue. Thus, applying these new measurement methods to study this group of experts may provide more insight into best ways to deal with fatigue, which could in turn help deal with, or even prevent, fatigue-associated injuries in a variety of populations.

RESEARCH ARTICLE

Sport-specific expertise effects on motor adaptations during a fatiguing repetitive shoulder task

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ABSTRACT

Background: Repetition and fatigue are two well-known risk factors for neck/shoulder injury development. Water polo and swimming are two overhead sports that involve repetitions and that may lead to fatigue. However, there is little research into how overhead sport expertise affects the muscle fatigue response, from both objective and subjective fatigue points of view.

Methods: Thirty-seven participants [14 controls (CNTL), 24.71 years (SD = 2.40); 12 swimmers (SW), 21.08 years (SD = 2.15); 11 water polo players (WP), 21.45 years (SD = 5.82)] performed a maximal prone internal rotation task, followed by a sport-specific experimental task devised to fatigue the neck/shoulder muscles. This task consisted of repetitive, concentric internal rotations at 42.5-57.5 percent of their maximal effort which continued until either reporting 8 on the modified Borg C10 scale for shoulder effort, or missing the allotted torque bandwidth 8 or more consecutive times. Surface electromyography (EMG) was collected every minute for six muscles (pectoralis major (PEC), anterior deltoid (AD), posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), and latissimus deltoid (LAT)), and intramuscular EMG was collected every minute for 3 muscles (supraspinatus (SS), infraspinatus (IS), and subscapularis (SUB)). EMG root mean square (RMS), coefficient of variation (CoV), median power frequency (MdPF), and normalized mutual information (NMI) were analyzed using the GEE statistical model, using sequential bonferroni corrected (SBC) p-values. Specifically, data was analyzed for effects of condition (minute 1, median minute, last minute), expert group (controls, swimmers, water polo players) and muscle.

Results: Water polo players exhibited a peak internal rotation torque that was 34.7% greater than the swimmers' and 62.8% greater than the controls' respective outputs, as well as lower time to task completion when compared to controls and swimmers (CNTL = 8.5minutes (SD = 6.04), SW = 6.5 minutes (SD = 3.61), WP = 4.0 minutes (SD = 0.77). All participants showed task-induced fatigue through increased RMS of the PEC and AD, decreased MdPF in all muscles, increased CoV for the deltoids, UT, and LAT, and overall increase in NMI from the first minute (NF) to last minute (FT) of task completion. Controls showed many differences from both swimmers and water polo players. They showed higher PD EMG RMS compared to swimmers (at NF) and compared to both swimmers and water polo players (at the median minute (MF)), higher PEC EMG RMS at MF compared to swimmers, and higher SUB EMG RMS at MF and FT compared to water polo

players. In addition, they showed higher SUB MdPF at NF compared to water polo players, and lower PEC MdPF at NF and FT compared to swimmers. Finally, they showed higher AD CoV at NF compared to swimmers, and higher AD CoV at MF compared to water polo players. As for swimmers, they showed lower UT CoV at NF compared to both controls and water polo players. As for inter-muscle functional connectivity, controls exhibited higher NMI involving the PEC compared to swimmers, and water polo players showed higher NMI involving the LAT and UT compared to both swimmers and controls.

Conclusions: Results suggest that with fatigue, each group implemented different adaptation strategies. Controls seemed to require higher activation and variability for their prime internal rotators and shared the load between internal rotators and scapular stabilizers in order to control the repetitive concentric internal rotations. In comparison, swimmers exhibited more repeatable patterns where fatigue may be isolated to specific muscles. Lastly, water polo players exhibited more variable patterns and evidence for synergies between internal rotators and scapular stabilizers as fatigue developed. Overall, findings suggest that fatigue adaptations to a common internal shoulder rotation task are expertise-specific.

1.0 Background

Chronic shoulder injuries are common among elite overhead athletes, with many reporting shoulder pain throughout their career and/or needing to temporarily interrupt training and/or competition due to a shoulder injury[5,22, 26,28]. Elite athletes are one type of expert population that constantly trains in a repetitive fashion with high levels of fatigue, with repetition and fatigue being two known risk factors for musculoskeletal injury development[1]. When performing overhead movements, athletes strive to achieve correct balance between mobility and stability in order to prevent injury[8]. However, maintaining this balance requires muscular strength, endurance, flexibility, and neuromuscular control, without which, functional instability will arise[25,26]. Prolonged repetitive and fatiguing environments often results in imbalance, which ultimately leads to improper scapular and humeral kinematics, which then cascades to affect muscle activation, coordination, force production, and decreased performance[6,7]. Micro trauma on surrounding soft tissues then arises due to continued movement under improper mechanics[8,9,14].

Two overhead sports where repetition, fatigue, and lack of shoulder stability are frequently seen are water polo and swimming. Swimmers undergo a very large training load. Most national-level swimmers train twice a day, 5 days a week, with a total distance of 60,000 – 80,000 meters per week and 30,000 shoulder rotations per week[2,3,29]. Not only do water polo players swim thousands of meters each week, but a lot of the swimming involves maintaining the head above water. In addition, athletes pass and/or shoot over 250 times per week at high velocities, which puts even more strain on the shoulder joint[4,47]. Although shoulder injuries are prevalent in elite overhead athlete, the healthy ones may have developed adaptation mechanisms to withstand the intense load for a longer time than the average individual. Understanding how these experts respond and deal with fatigue may be beneficial to injury prevention.

Muscular fatigue is most commonly described as an exercise-induced response which leads to a decrease in the muscle's maximal capacity, which is further combined with an increase in perceived difficulty[10,11]. Electromyography (EMG) is a commonly used method to measure muscle fatigue, and specific changes in EMG measures have been associated with signs of localized muscle fatigue in a repetitive, submaximal, dynamic task, the most common ones being a decrease in median power frequency (MdPF) as well as an increase in amplitude[10,12] (eg. root mean square (RMS)) Another commonly observed feature of the motor system linked to the presence of fatigue in repetitive movements is motor variability, defined as an individual's natural variation in muscle activity, and which can be quantified from the EMG by calculating the standard deviation (SD) across the RMS data of repeated task cycles and normalizing to the corresponding average RMS to obtain the coefficient of variation (CoV)[16]. Higher motor variability is thought to help slow fatigue and injury development, reduce the load on fatiguing tissues, and help preserve performance[14-16]. The majority of studies suggest that fatigue elicits and increase in variability[53,57,60,61,62]. Moreover, experience/expertise in performing specific tasks or movements has also been suggested to influence motor variability. although this is thought to be task-dependent. In studies investigating dynamic, repetitive tasks which allow for more freedom of movement, experts have shown higher variability, which suggests that they have a better ability to search for new motor solutions to preserve task performance[63,64,65]. In studies measuring variability in tasks that were more constrained, more sport-skill specific, and included a precision component, experts have shown lower variability due to the need to stay consistent to maintain performance[67-69]. The majority of studies investigating EMG variability are ergonomics studies[16], whereas in sports sciences, the majority have so far investigated kinematic or kinetic variability, with little information on experts' EMG variability.

Other types of EMG measures that have been evaluated in connection with fatigue describe how two muscles pairs coordinate. Normalized mutual information (NMI) is defined as the amount of "functional or shared connectivity between two muscles[72]." Unlike other similar methods such as cross-correlation, this statistical method uses both linear and non-linear relationships to quantify co-ordination patterns between muscles[73,74]. Past research on NMI differences seen with fatigue, gender, injury, and/or task type are contradictory, with higher functional connectivity seen in women and in isometric tasks and lower functional connectivity found in dynamic tasks and injured individuals[17,57, 72,76,77,78]. Moreover, higher connectivity is thought to be linked to a strategy of sharing the fatiguing load between muscle pairs, or helping maintain joint stability, whereas lower connectivity is interpreted as a way to isolate fatigue to one muscle in order to prevent spreading of fatigue symptoms[17,18,19]. However, the literature is yet inconclusive as to whether NMI reflects beneficial or poor strategies regarding injury development. Moreover, to our knowledge, no study has investigated the effects of expertise on functional connectivity in a fatiguing task.

The general objective of this study was to determine if aquatics sport-specific expertise has an effect on EMG related fatigue measures during a repetitive, submaximal, prone shoulder internal rotation task. First, we hypothesized that both water polo and swimming expert groups would perform the fatiguing task longer before reaching the fatigue criteria compared to the controls, however swimmers would last the longest out of the three groups. Second, we hypothesized that fatigue would be associated with increases in amplitude, motor variability, and mutual information as well as decreases in frequency amongst the various neck/shoulder muscles and muscle pairs. Third, we hypothesized that amplitude would be higher and frequency would be lower in controls compared to both expert groups with swimmers having lower amplitude and higher frequency than water polo players. Fourth, we hypothesized that both expert groups would have higher levels of variability compared to controls, however water polo players would have the highest levels of motor variability. Lastly, we hypothesized that both expert groups would have higher functional connectivity than controls at all time points, however swimmers would have the highest levels of functional connectivity with fatigue.

2.0 Methods

2.1 Participants

A convenience sample of 37 healthy female volunteers was recruited from University, Sports Canada, and local community networks. Participants were excluded from the study if they had a history of musculoskeletal injuries affecting the shoulder/neck region or neurological conditions that could affect task performance. The participants were assigned to either one of three groups: controls (CNTL), expert swimmers (SW), and expert water polo players (WP). The term 'expert in aquatic repetitive upper limb movement' was defined as an individual who has 6 or more years of experience at the national or international level in either swimming or water polo and participates in aquatic training ≥15 hours per week[79]. Participants who were experts in other repetitive upper limb sports, for example, volleyball, were excluded from participation. The study was performed at the National Institute of Sport in Quebec (INS) in Montreal, Quebec. Prior to partaking in the study, all participants provided informed consent approved by the Research Ethics Board of the Center for Interdisciplinary Research in Rehabilitation (CRIR) of Greater Montreal.

2.2 Experimental Protocol

After completing the written consent forms [Appendices 1 (English), 2 (French)], descriptive information (age, experience) and anthropometric measurements (height, weight) were recorded. The modified Borg-CR10 Scale used by Borg (1982) [Appendices 3 (English), 4 (French)] was described in the same manner to each participant to ensure consistency in their understanding. In our study, the scale was only used to report the RPE for the neck/shoulder area.

2.21 Isokinetic Dynamometer Set Up

The participant was brought over to the Con-Trex Multi-Joint Isokinetic Dynamometer (Con-Trex MJ; CMV AG, Dubendorf, Switzerland) where they were set up in the desired positioning and the machine was adjusted to match their individual anthropometric measurements. First, the seat was laid flat and the participant was asked to lie in prone position, while the machine was adjusted to take measurements from their right arm. Depending on how long their arm was, the seat was rotated between 20-35 degrees counter-clockwise. The motor was secured to the open end of the Con-Trex on the participant's right side and the side opposite the rotation of the seat. In the prone position, the participant was instructed to abduct their right upper arm to 90, so that their shoulder and elbow joint were in line with the motor. Further, they were asked to let their forearm hang perpendicular to their body, with their fingers pointed towards the ground[80]. The motor was moved, rotated, raised, and/or lowered in order to line up with the humerus and glenohumeral joint. To maintain elevation of the chest and shoulder joint and to prevent contact between the pectoralis major muscle and the seat, the participant's chin rested on a stack of towels. Each participant's seat rotation and motor position were documented. Next, the zero-position of the motor was found by following the instructions from the Con-Trex software. After finding the zero-position, the long-arm adapter was fastened to the motor, along with the elbow support and handle adapters. The participant was asked to fit their arm into the elbow adapter and hold the wrist adapter. The wrist adapter was either moved closer to or further from the elbow adapter to make sure that the participant's elbow was tightly fixed within the support padding of the elbow adapter. Double checks were done to confirm that the participant's was still in the correct positioning **(Figure 1).** The attachment range of motion (ROM) was set to 80° according to the degree markings on the motor. Zero-position was set as the end range for internal rotation and 80° was set as the end range for external rotation. The 'Measurement' setting was used to collect a new sample with a sampling frequency of *4000 Hz*, with the torque set to 125nm, and the speed set to 120° per second. Pilot testing based on a study by Falkel, Murphy, & Murray (1987) that used different positions on an isokinetic dynamometer to measure torque output in swimmers determined that 120° per second both most closely matched swimming stroke speed as well as produced the highest torque output.

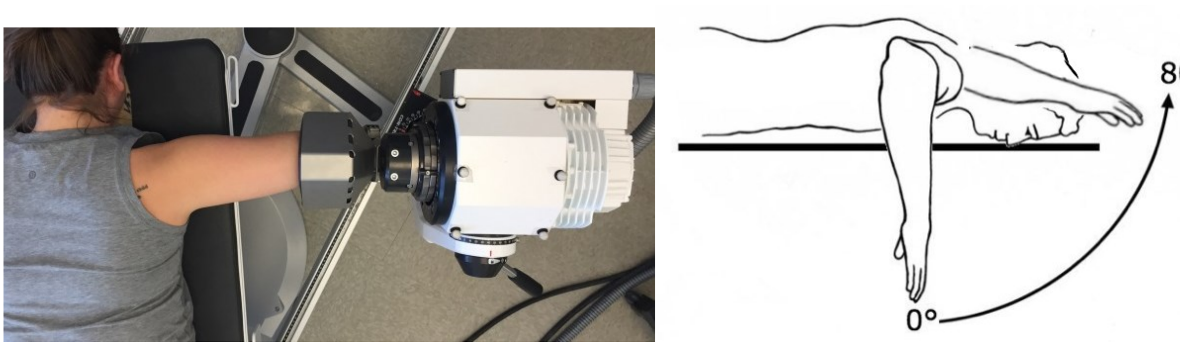

Figure 1. Left: Subject positioning on the CON-TREX, with their shoulder joint in line with the motor. Right: The range of motion performed by the motor and attachments (80 degrees in internal/external rotation).

To ensure that the data collection was consistent, a baseline value was collected for the weight of the participants arm in the machine. To do this, the participant was instructed to relax and let their arm be passively moved as the motor moved the machine through the entire ROM two times. To familiarize the participant, we set the machine to move on its own through both external and internal rotation for 10 repetitions. The participant was asked to first feel the speed and movement, and then begin to do concentric internal and external rotations with the machine.

2.22 EMG Preparation

Next, the participant was prepared for EMG data collection. We used a Delsys measurement system (Delsys Trigno Wireless EMG, Natick, MA, USA) with Trigno™ Standard wireless sensors, at an operating bandwidth of 15 to 500Hz, and a sampling frequency of *2000 Hz*. Intramuscular EMG was used to record muscle activation of the supraspinatus (SS), infraspinatus (IS), and subscapularis (SUB) muscles. To record intramuscular EMG, the muscle sites were first sterilized with betadine, then, using gloves, the paired hook-wire electrodes were inserted into the muscle using a single-use, 0.05mm wide needle as the applicator. The wires were insulted with nickel alloy up to the lase 2mm and connected to intramuscular adapted sensors which were placed 2 cm away from the insertion point. The insertion points are described below in **Table 1**[81]. Then, skin sites for surface electrodes to record from the pectoralis major (PEC), anterior deltoid (AD), posterior deltoid (PD), upper trapezius (UT), middle trapezius (MT), and latissimus dorsi (LAT) were identified, marked, and prepared (shaved and cleaned with alcohol). Surface electrodes were placed on those six muscles according to **Table 1** below. The Trigno™ surface sensors provide a fixed distance of 10mm between the electrodes. The electrodes were positioned such that the line between each sensor's bipolar electrodes was oriented parallel to muscle fibers. All electrodes were secured with double sided tape on the bottom and medical tape over the top.

Muscle	*Electrode Position*
	Surface EMG
R. Pectoralis Major	Placed three finger widths below slightly proximal the coracoid process of the shoulder.
R. Anterior Deltoid	Placed one finger width distal and anterior to the acromion.
R. Posterior Deltoid	Placed two finger widths behind the angle of the acromion.
R. Upper Trapezius	Placed on the midpoint between the C7 spinous process and the anterior acromion process.
R. Middle Trapezius	Placed on the midpoint between the medial border of the scapula and the spine, at the level of T3.
R. Latissimus Dorsi	Placed 4 finger widths under the armpit, distal to the edge of the scapula.
	Intramuscular EMG
R. Supraspinatus	Placed 1 1/2 cm superior to the midpoint of the spine of the scapula.
R. Infraspinatus	Placed 2.5 cm inferior to the midpoint of the spine of the scapula
R. Subscapularis	Placed 5 cm below the below the spine of the scapula, anterior to the medial border, directed perpendicular to the medial border

Table 1. EMG Electrode Placement

2.23 Maximal Voluntary Reference Contractions (MVRC)

After the EMG electrodes were fitted, the participants were instructed to repeated the 10-repetition familiarization, however this time increasing their pushing and pulling intensity with each repetition, ending with their maximal effort. After, they were asked to perform MVRCs in internal rotation. The participant was instructed to perform 3 repetitions of maximal effort internal rotation followed by passive external rotation with the motor moving at 120° per second. The participant's legs were secured to the seat with the seatbelt attachments. This was done to ensure that participant was not using their legs to assist their upper body during the MVRCs. This was repeated two times with 60 seconds rest between each. To ensure maximal-force production, the researchers gave vocal encouragement. Following this procedure, A MATLAB (Mathworks, Natick, MA, USA) script was created and used to calculate a 42.5-57.5% MVRC bandwidth, that was then to be used in the fatiguing protocol.

2.24 Fatiguing Protocol

Once the MVRCs were completed, the subjects performed the continuous submaximal internal rotation fatiguing task (IRFT) protocol. The IRFT consisted of performing continuous submaximal concentric internal rotation followed by passive external rotation with the Con-Trex motor moving at 120° per second, at a torque output within the 42.5 – 57.5% MVRC bandwidth, until the participant met at least one of the termination criteria. A monitor was set up on the ground in front of the open end of the Con-Trex, in the participant's direct eye sight, with an image of the calculated bandwidth **(Figure 2)**.

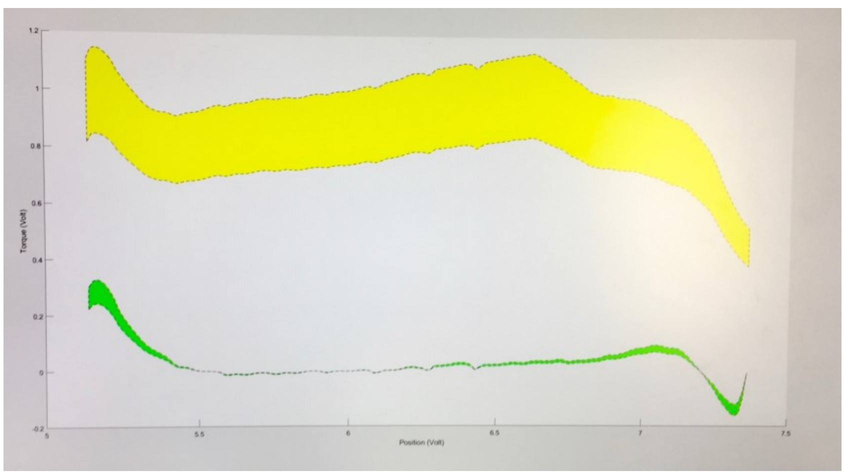

Figure 2. Shows the 42.5-57.5% internal rotation bandwidth (yellow) used in the IRFT, which was calculated using the MVRC torque values at each position. The green band is the exact values of the external rotation from the MVRC.

Each repetition, a thin black line showed live feedback of the participant's torque values as they went through internal and then external rotation. Before starting the IRFT, each participant was familiarized to the task. The participant was instructed to keep their black line within the yellow internal rotation bandwidth to the best of their ability. The participant completed a maximum of 3 familiarization trials until the researchers were confident that the participant both understood the task and could adequately maintain their torque values within their bandwidth. Each familiarization trial was capped at 20 seconds and was performed a maximum of 3 times, with a 60 second rest period between each to ensure that the participant was not being fatigued. Once familiarized, the participant was given specific instructions to follow for the IRFT protocol. They were told that the goal was the same as for the familiarization task: maintain their internal rotation torque within their bandwidth to the best of their ability while relaxing in external rotation. During the first 20 seconds of every minute, one of the researchers coached the participant to ensure that they stayed within their bandwidth. For the next 30 seconds, the participant was told to "stay constant," meaning that they were on their own without instruction. At the end of those 30 seconds, the subject was asked to rate their shoulder perceived effort on the Borg CR10 Scale.

For the remaining 10 seconds of each minute, the black line would disappear while we saved the collected data from the previous 50 seconds. However, the subject was instructed to continue pushing internally at the same effort. Once the subject self-reported 8/10 or higher or missed their bandwidth during eight or more consecutive movement cycles, the session was terminated. The subject was not aware of the stoppage criteria prior to the fatiguing protocol.

2.3 Data Analysis

Time-To-Fatigue (TTF) was calculated as the number of minutes the fatiguing task was performed. All EMG data was filtered using a zero-lag 2nd-order Butterworth bandpass filter. The surface EMG data was band-passed between 10 and 450 Hz and the intramuscular EMG signals were band-passed between 10 and 1000 Hz. Further, the intramuscular EMG data underwent a notch filter to remove frequency harmonics. The signal was then rectified and the EMG RMS was obtained using a moving window with a length of 100ms. This calculation was done by squaring all values in the window, determining the mean of the resultant values, and then taking the square root of the result to get one value for each time point. For the MdPF calculations, a Fast Fourier Transformation (FFT) was applied to the filtered EMG signal using a 100ms moving window, then the Power Spectrum Density was obtained by squaring the FFT and determining the magnitude. Finally, the MdPF was calculated by finding the frequency value that divides the PSD in two regions having the same power. The 30 second block where the participant was without coaching was partitioned into internal and external rotations using the Con-Trex position data. The EMG data from the IRFT was normalized to MVRC EMG data and one EMG RMS value was calculated for each internal rotation by taking the area under the EMG RMS curve for each internal rotation partition. Similarly, one MdPF value was calculated for each internal rotation by taking the median frequency for each internal rotation partition. The EMG and MdPF RMS values for the middle ten internal rotations were averaged to generate a single RMS value for each trial for each muscle. For each trial and each muscle, EMG RMS CoV was calculated by dividing the standard deviation by the average of the EMG RMS values for the middle ten internal rotations. Lastly, NMI was analyzed for the possible pairs between the four internal rotator muscles and the possible pairs between the four internal rotator muscles and 5 scapular stabilizer muscles. NMI corresponds to the amount of functional connectivity between two muscle pairs, with a value of 0 corresponding to 'no connectivity', and 1 to 'complete connectivity' (for further details on calculations, please see (Jeong, Gore, & Peterson (2001) and Kojadinovic (2005)). The NMI values for the middle ten internal rotations were averaged to generate a single NMI value for each trial for each muscle pair. For all EMG RMS, EMG MdPF, CoV and NMI variables, three conditions, representing each subject's different times during their fatigue sequence, were evaluated for this project:

- NF – data from the first minute
- MF – data from the median minute (between the first minute and the last minute). If the participant had an even number of trials, the values from the middle two trials were averaged.
- FT - data from the final minute after which the fatigue task was completed.

2.4 Statistical Analysis

Descriptive statistics were recorded from each participant. An ANOVA with post-hoc Tukey tests was run for anthropometric (height, weight, BMI) data to evaluate group differences. A Generalized Estimating Equation (GEE Model) was applied to all EMG variables (RMS, MdPF, CoV, and both set of NMI pairs) separately. The first model contained two within-subject variables [Condition, 3 levels (NF, MF, FT); Muscle, 9 levels], one between-subject variable [Expert Group, 3 categories (control, swimmer, water polo)], and was used to evaluate RMS, MdPF, and COV interactions. The second model contained two within-subject variables [Condition, 3 levels (NF, MF, FT); Muscle Pairs, 6 levels (for internal rotator pairs) and 19 levels (for internal rotator and stabilizer pairs)], one between-subject variable [Expert Group, 3 categories (control, swimmer, water polo)], and was used to evaluate both sets of NMI interactions. A pairwise comparison with Sequential Bonferroni Correction (SBC) was further applied for the statistically significant overall effects. SPSS (IBM Corp. Released 2015. IBM SPSS Statistics for Windows, Version 23.0. Armonk, NY) was used, tested at probability alpha level of 0.05.

3.0 Results

3.1 Descriptive Statistics

Our sample included: 14 controls, 12 expert swimmers, and 11 expert water polo players. 35 out of 37 participants were right-hand dominant. The inter-individual variability for descriptive characteristics is shown in **Table 2**. An ANOVA showed that there were significant group differences for experience [$F(2,34) = 45.94$, $p < 0.001$], Age [$F(2,34) = 3.83$, $p = 0.032$], weight [$F(2,34) = 7.68$, $p = 0.002$], and BMI [$F(2,34) = 6.55$, $p = 0.004$]. Post-hoc Tukey comparisons showed that controls had significantly less experience than both swimmers and water polo players but that there was no difference in experience between the two expert groups, that controls were significantly older than swimmers, and that water polo players had significantly higher weight and BMI than both swimmers and controls.

Expert Group	Experience (years)	Age (years)	Height (cm)	Weight (kg)	BMI	Time to Fatigue (minutes)	MVRC Peak IR Torque
CNTL	**0 (0)**[bc]	**24.71(2.40)**[c]	166.72(6.83)	**63.43(9.77)**[b]	**22.85(3.49)**[b]	**8.5(6.04)**[b]	**18.61 (4.8)**[b]
SW	**12.83(3.41)**[c]	**21.08(2.15)**[c]	169.1(4.67)	**67.85(6.35)**[a]	**23.74(1.68)**[a]	6.5(3.61)	**22.48(3.73)**[a]
WP	**10.73(5.76)** [b]	21.45(5.82)	171.49(6.9)	**79.95(14.75)** [ab]	**27.03(3.3)**[ab]	**4(0.77)**[b]	**30.29(9.93)**[ab]

Table 2. Descriptive statistics for all participants. Values are mean (SD). [a]: different between WP and SW; [b]: different between CNTL and WP; [c]: different between CNTL and SW; *: overall group effect; CNTL: controls; SW: swimmers; WP: water polo players; BMI: body mass index; MVRC: maximal voluntary reference contraction; IR: internal rotation

3.2 Time-To-Fatigue and MVRC Peak IR Torque

Participants completed the IRFT for an average duration of 6.51 ± 4.56 minutes. An ANOVA showed that there were significant group differences for time-to-fatigue [$F(2,34) = 3.41$, $p = 0.045$] and MVRC peak IR torque [$F(2,34) = 10.2$, $p = 0.003$]. Post-hoc Tukey comparisons showed that water polo players ($M = 4.0$, $SD = 0.77$) performed the task for significantly less time than the controls ($M = 8.5$, $SD = 6.04$). However, water polo players did not differ from swimmers ($M = 6.5$, $SD = 3.61$) in time-to-fatigue. Further, post-hoc Tukey comparisons showed that water polo players ($M = 30.29$, $SD = 9.93$) pushed a significantly larger MVC peak IR torque than both swimmers (M = 22.38, SD = 3.73) and controls (M = 18.61, SD = 4.8), however swimmers did not differ from controls.

3.3 RMS Amplitude

Significant Expert Group * Condition * Muscle effects were found for PD, PEC, and SUB EMG RMS **(Figure 3)**. Controls showed a higher PD EMG RMS [Contrast Estimate (CE) = 12.67; Standard Error (SE) = 3.56; SBC = 0.001] compared to swimmers in the NF condition. In addition, controls exhibited a higher PD RMS compared to both swimmers [CE = 7.80; SE = 3.26; SBC = 0.033] and water polo players [CE = 7.80; SE = 3.26; SBC = 0.005] in the MF condition. Controls also had a higher PEC RMS [CE = 10.52; SE = 4.19; SBC = 0.036] compared to swimmers in the MF condition. Lastly, controls exhibited a higher SUB RMS compared to water polo players in both the MF [CE = 12.69; SE = 5.27; SBC = 0.048] and FT [CE = 15.88; SE = 5.82; SBC = 0.019] conditions.

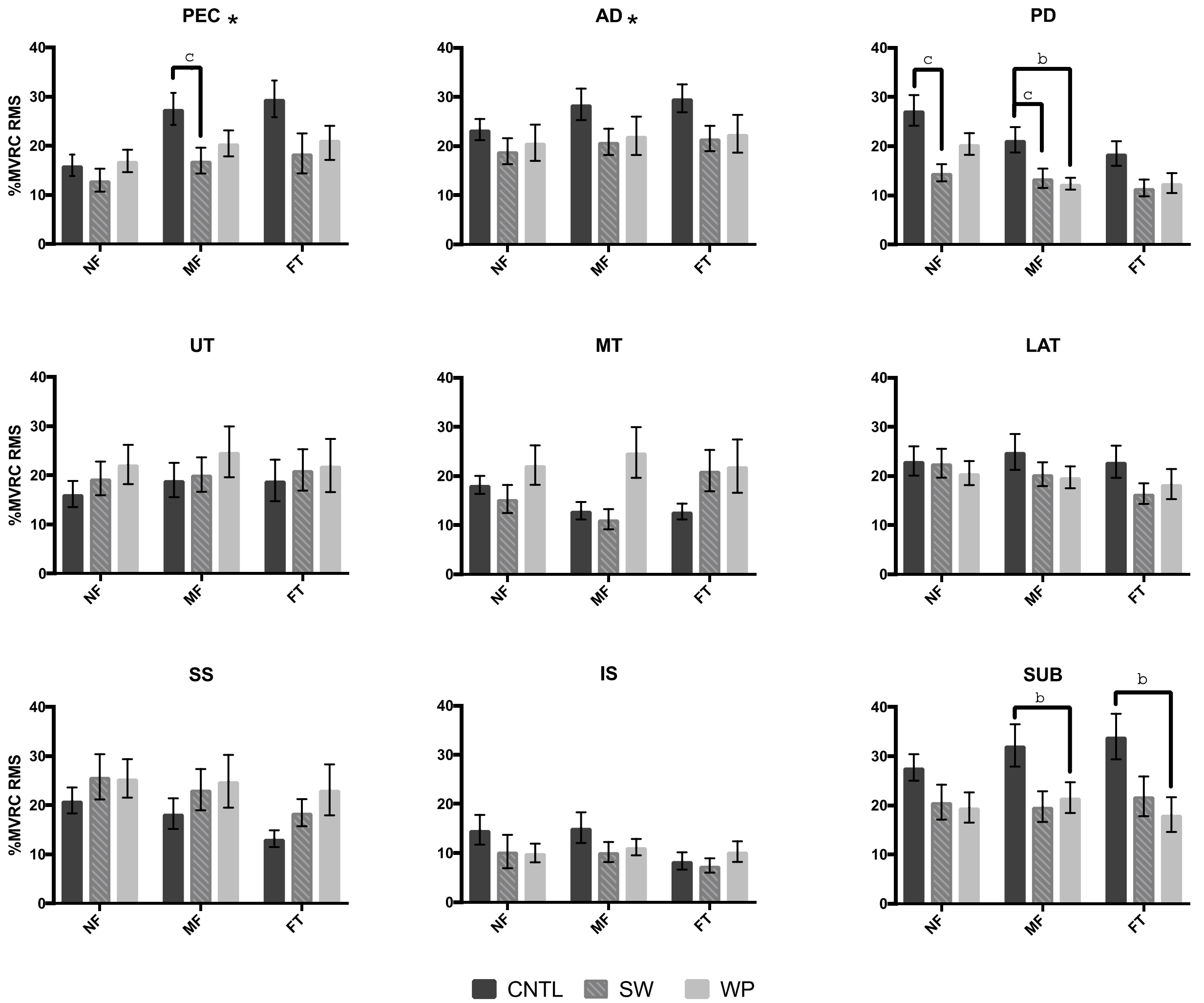

Figure 3. Group mean (SE) EMG RMS Amplitude for nine shoulder muscle at three time conditions (NF, MF, FT), displayed for control (dark grey), swim (striped gray), and water polo (light gray) groups. [a]: Expert Group*Condition*Muscle effect between WP and SW; [b]: Expert Group*Condition*Muscle effect between CNTL and WP; [c]: Expert Group*Condition*Muscle effect between CNTL and SW; ***:** Condition*Muscle effect

Significant Condition * Muscle effects were found for PEC and AD EMG RMS. The PEC [CE = -7.75; SE = 1.61; SBC = 0.00] and AD [CE = -4.12; SE = 1.29; SBC = 0.004] had increases in RMS amplitude as a function of Condition.

3.4 EMG MdPF

Significant Expert Group * Condition * Muscle effects were found for PEC and SUB EMG MdPF **(Figure 4)**. Controls showed a lower PEC EMG MdPF compared to swimmers in the NF [CE = -9.36; SE = 3.34; SBC = 0.015] and FT conditions [CE = -9.37; SE = 3.18; SBC = 0.010].

Moreover, controls exhibited a higher SUB MdPF compared to water polo players [CE = -42.81; SE = 16.27; SBC = 0.026] in the NF condition.

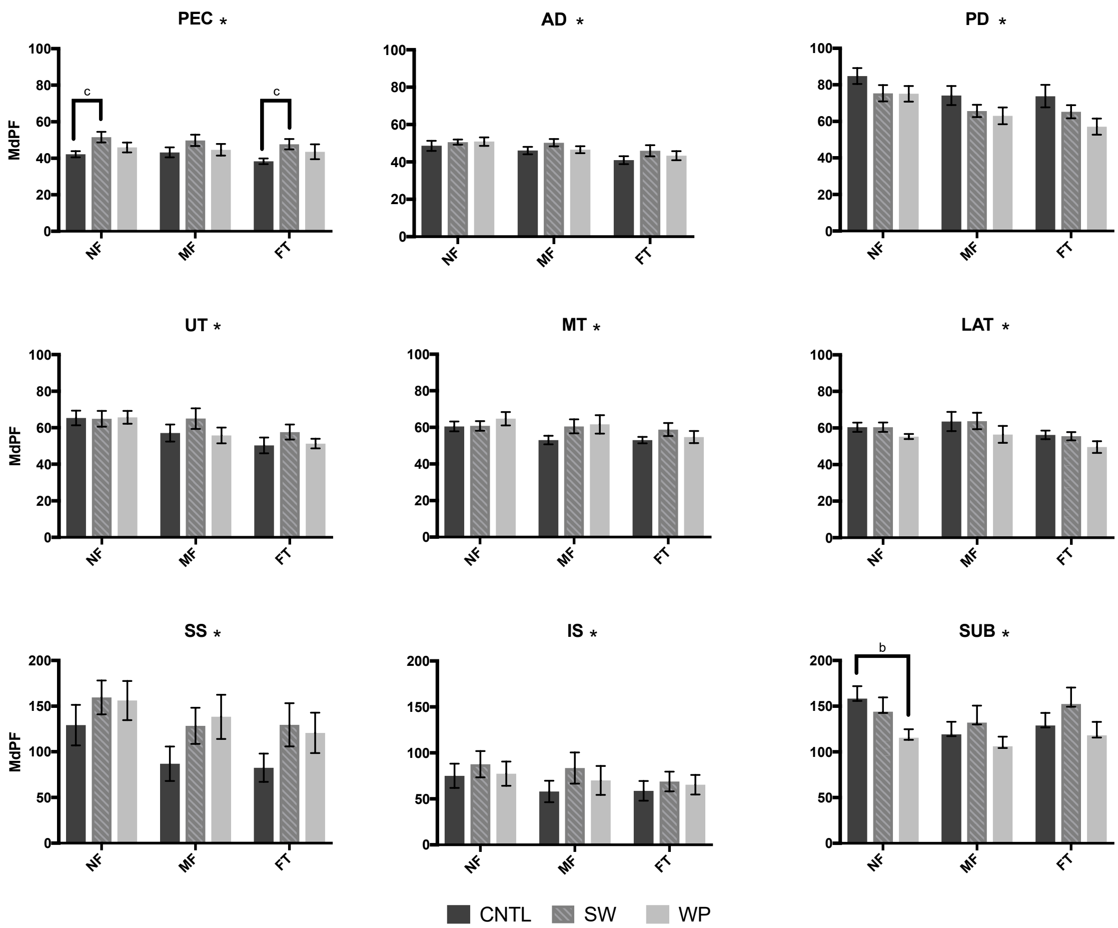

Figure 4. Group mean (SE) EMG MdPF (expressed in Hz) for nine shoulder muscle at three time conditions (NF, MF, FT), displayed for control (dark gray), swim (striped gray), and water polo (light gray) groups. [a]: Expert Group*Condition*Muscle effect between WP and SW; [b]: Expert Group*Condition*Muscle effect between CNTL and WP; [c]: Expert Group*Condition*Muscle effect between CNTL and SW; *: Condition*Muscle effect;

Significant Condition * Muscle effects were found for all muscle's EMG MdPF. The PEC [CE = -3.38; SE = 1.12; SBC = 0.008], AD [CE = -6.61; SE = 1.68; SBC = 0.00], PD [CE = 10.80; SE = 1.94; SBC = 0.00], UT [CE = 6.01; SE = 2.38; SBC = 0.014], MT [CE = 6.52; SE = 1.16; SBC = 0.004, LAT [CE = -4.95; SE = 1.25; SBC = 0.00], SS [CE = 37.34; SE = 11.05; SBC = 0.002], and IS [CE = 15.71; SE = 5.78; SBC = 0.02] all showed decreases in MdPF as a function of Condition. The SUB [CE = 20.18; SE = 7.24; SBC = 0.016] had a decrease in MdPF from the MF to FT condition.

3.5 Muscle activity CoV

Significant Expert Group * Condition * Muscle effects were found for AD and UT CoV **(Figure 5)**. Controls showed a higher AD CoV compared to swimmers in the NF condition [CE = 0.083; SE = 0.033; SBC = 0.039] and compared to water polo players in the MF condition [CE = 0.059; SE = 0.024; SBC = 0.043]. Swimmers also showed lower CoV for the UT compared to both controls [CE = 0.072; SE = 0.032; SBC = 0.047] and water polo players [CE = -0.04; SE = 0.016; SBC = 0.040] in the NF condition.

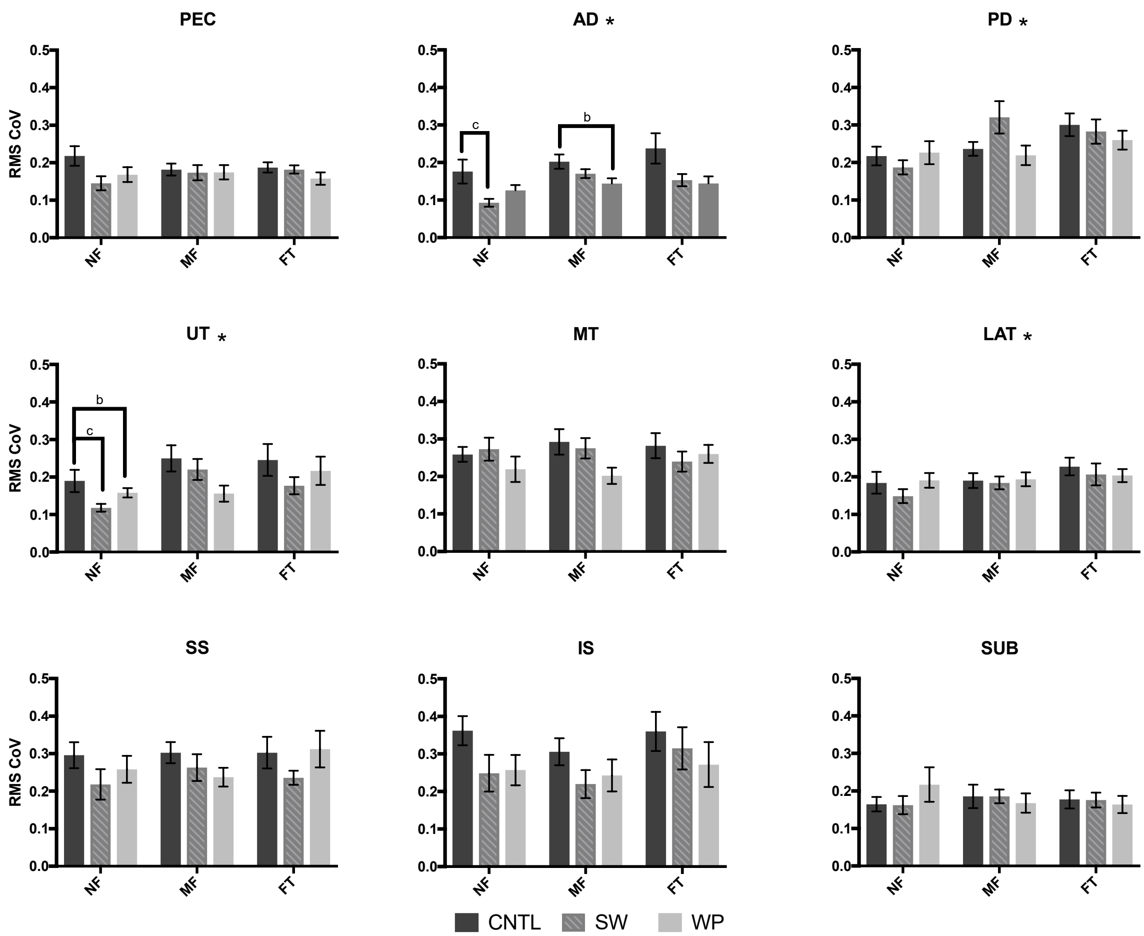

Figure 5. Group mean (SE) EMG RMS CoV for nine shoulder muscle at three time conditions (NF, MF, FT), displayed for control (dark gray), swim (striped gray), and water polo (light gray) groups. [a]: Expert Group*Condition*Muscle effect between WP and SW; [b]: Expert Group*Condition*Muscle effect between CNTL and WP; [c]: Expert Group*Condition*Muscle effect between CNTL and SW; ***:** Condition*Muscle effect;

Significant Condition * Muscle effects were found for AD, PD, UT, and LAT CoV. The AD [CE = -0.063; SE = 0.023; SBC = 0.014], PD [CE = -0.071; SE = 0.02; SBC = 0.001], UT [CE = -0.053; SE = 0.021; SBC = 0.013], and LAT [CE = -0.038; SE = 0.016; SBC = 0.045] had increases in CoV as a function of Condition.

3.6 NMI Between Internal Rotator Muscles

Significant Expert Group * Condition * Muscle Pair effects were found for LAT_PEC and LAT_SUB NMI. Swimmers showed lower LAT_PEC NMI compared to controls and water polo players in the MF and FT conditions. As well, swimmers exhibited lower LAT_SUB NMI compared to water polo players in the FT condition. Statistical values can be found in **Table 3**.

Statistics for Internal Rotator Model

		CNTL vs. SW			CNTL vs. WP			SW vs. WP		
		CE	SE	SBC	CE	SE	SBC	CE	SE	SBC
AD_LAT*	NF	-0.0031	0.00367	0.803	0.0025	0.00362	0.803	0.0056	0.00412	0.516
	MF	-0.0062	0.00403	0.252	-0.0089	0.00396	0.075	-0.0027	0.00374	0.471
	FT	-0.0028	0.00483	0.568	-0.0102	0.00499	0.123	-0.0074	0.00535	0.329
AD_PEC*	NF	-0.0034	0.00498	1	-0.0018	0.00484	1	0.0016	0.00586	1
	MF	-0.0006	0.00544	1	-0.0006	0.00544	1	0	0.0044	1
	FT	0.0045	0.00505	0.744	-0.0019	0.00562	0.744	-0.0064	0.00454	0.478
AD_SUB	NF	-0.0106	0.00716	0.42	-0.004	0.00492	0.821	0.0065	0.00794	0.821
	MF	-0.0155	0.00704	0.083	-0.0077	0.00656	0.482	0.0078	0.00789	0.482
	FT	-0.0038	0.00587	0.644	-0.0107	0.00689	0.357	-0.007	0.00704	0.644
LAT_PEC*	NF	0.0024	0.00328	0.565	-0.0039	0.00361	0.565	-0.0063	0.00388	0.317
	MF	.0078	0.00298	***0.018***[c]	-0.0055	0.00399	0.166	-.0133	0.00368	***0.001***[a]
	FT	.0105	0.00417	***0.024***[c]	-0.0058	0.00503	0.25	-.0162	0.00442	**0.001**[a]
LAT_SUB	NF	-0.0002	0.00354	0.954	-0.0072	0.00358	0.136	-0.007	0.004	0.164
	MF	0.0033	0.00407	0.424	-0.0072	0.00398	0.139	-0.0105	0.00454	0.063
	FT	0.0093	0.00459	0.087	-0.0068	0.00432	0.118	.0160	0.00475	**0.002**[a]
PEC_SUB*	NF	0.0015	0.00442	0.739	-0.0088	0.00554	0.31	-0.0103	0.00631	0.31
	MF	0.0039	0.00537	1	-0.0042	0.00887	1	-0.0081	0.00873	1
	FT	0.0114	0.00596	0.113	-0.0055	0.00832	0.511	-0.0168	0.00773	0.088

Table 3. Confidence estimate (CE), Standard Error (SE), and Sequential Bonferroni Coefficient (SBC) for NMI Statistical Analysis of Internal Rotators Model. [a]: Expert Group*Condition*Muscle effect between WP and SW; [b]: Expert Group*Condition*Muscle effect between CNTL and WP; [c]: Expert Group*Condition*Muscle effect between CNTL and SW; *****: Condition*Muscle effect;

Significant Condition * Muscle Pair effects were found for AD_LAT, AD_PEC, LAT_PEC, and PEC_SUB NMI. The AD_LAT [CE = -0.005; SE = 0.002; SBC = 0.032], LAT_PEC [CE = -0.005; SE = 0.0018; SBC = 0.014], and PEC_SUB [CE = -0.008; SE = 0.003; SBC = 0.007] NMI increased as a function of Condition. As well, the AD_LAT [CE = -0.006; SE = 0.002; SBC = 0.001] increased from NF to MF conditions.

3.7 NMI Between Internal Rotator and Stabilizer Muscles

Significant Expert Group * Condition * Muscle Pair effects were found for AD_UT, LAT_MT, LAT_SS, LAT_SUB, LAT_UT, PEC_MT, and PEC_SS NMI. Swimmers showed lower LAT_MT and LAT_SUB NMI compared to water polo players in both MF and FT conditions. As well, water polo players exhibited higher LAT_UT NMI compared to both controls and swimmers in the MF and FT conditions. Further, swimmers showed lower PEC_MT and PEC_SS NMI compared to controls in the MF condition. Lastly, water polo players showed higher AD_UT NMI compared to controls in the FT condition. Statistical values for the aforementioned statistically significant muscle pairs can be found in **Table 4**. To note, AD_IS, AD_MT, AD_SS, AD_SUB, IS_LAT, IS_PEC, IS_SUB, LAT_SS, MT_SUB, PEC_SUB, PEC_UT, SS_SUB, SUB_UT did not significantly change with condition or expertise.

		Statistics for Significant Muscle Pairs in Internal Rotator & Stabilizer Model								
		CNTL vs. SW			CNTL vs. WP			SW vs. WP		
		CE	SE	SBC	CE	SE	SBC	CE	SE	SBC
AD_UT	NF	-0.0128	0.01088	0.721	-0.0003	0.00874	0.969	-0.0131	0.0124	0.721
	MF	-0.0252	0.01297	0.157	0.0121	0.00736	0.201	-0.0131	0.01322	0.321
	FT	-0.0208	0.0107	0.105	.0227	0.00647	***0.001***[b]	0.002	0.01092	0.858
LAT_MT	NF	-0.0014	0.00333	1	0.0021	0.00434	1	0.0007	0.00411	1
	MF	0.0025	0.00411	0.546	0.0083	0.00465	0.147	.0108	0.00342	***0.005***[a]
	FT	0.0061	0.00524	0.487	0.0055	0.00647	0.487	.0116	0.00458	***0.033***[a]
LAT_SS	NF	0.0078	0.00511	0.387	-0.0078	0.0054	0.387	0	0.00422	0.991
	MF	0.0093	0.00593	0.232	0.002	0.00694	0.771	0.0113	0.00572	0.143
	FT	0.0076	0.00615	0.548	-0.0001	0.00593	0.983	0.0075	0.00563	0.548
LAT_SUB	NF	0.0007	0.00341	0.847	0.0074	0.00362	0.121	0.008	0.00393	0.121
	MF	0.0041	0.00398	0.301	0.0075	0.00415	0.145	.0116	0.00461	***0.036***[a]
	FT	0.0101	0.00452	0.051	0.007	0.00444	0.115	.0171	0.00479	***0.001***[a]
LAT_UT	NF	-0.002	0.0033	1	0.0032	0.00371	1	0.0012	0.00401	1
	MF	-0.0012	0.00444	0.787	.0103	0.0038	***0.021***[b]	.0091	0.0037	***0.028***[a]
	FT	0.0017	0.00474	0.727	.0122	0.00419	***0.008***[b]	.0138	0.00354	***0***[a]
PEC_MT	NF	0.0029	0.00325	1	-0.0015	0.00371	1	0.0014	0.00377	1
	MF	.0099	0.00394	***0.036***[c]	-0.003	0.00474	0.526	0.0069	0.00417	0.195
	FT	0.0114	0.0051	0.077	-0.0053	0.00542	0.328	0.0061	0.00401	0.261
PEC_SS	NF	0.0125	0.00598	0.109	-0.0056	0.00595	0.381	0.0069	0.00526	0.381
	MF	.0192	0.00661	***0.011***[c]	-0.0069	0.00752	0.358	0.0123	0.00604	0.085
	FT	0.0169	0.00889	0.174	-0.0123	0.00735	0.188	0.0046	0.00772	0.554

Table 4. Confidence estimate (CE), Standard Error (SE), and Sequential Bonferroni Coefficient (SBC) for NMI Statistical Analysis of Internal Rotators & Stabilizers Model. [a]: Expert Group*Condition*Muscle effect between WP and SW; [b]: Expert Group*Condition*Muscle effect between CNTL and WP; [c]: Expert Group*Condition*Muscle effect between CNTL and SW; *****: Condition*Muscle effect; for a definition of all muscle acronyms, please see text. All pairs analyzed but not displayed in this table showed no significant effects.

Significant Condition * Muscle Pair effects were found for many pairings between internal rotators and stabilizers. Indeed, AD_IS, AD_MT, AD_SS, AD_UT, IS_PEC, LAT_MT, LAT_SS, LAT_UT, MT_PEC, MT_SUB, PEC_SS, PEC_SUB, PEC_UT, SS_SUB, and SUB_UT NMI all increased as a function of condition **(Figure 6),** whereas AD_SUB, IS_LAT, IS_SUB, and LAT_SUB did not significantly change with Condition.

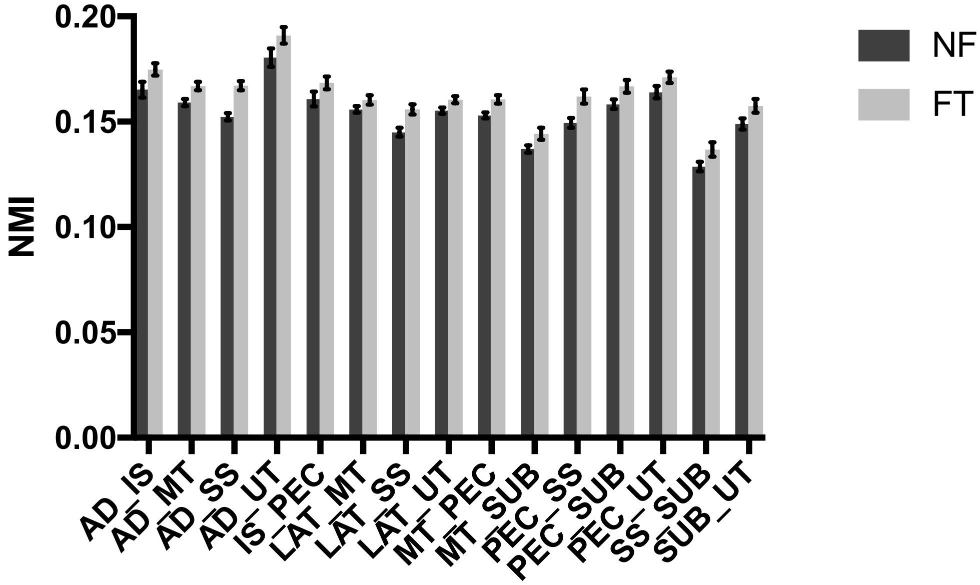

Figure 4. Collapsed group mean (SE) EMG NMI displayed for fifteen muscle pairs displaying significant Condition*Muscle pair effects for NF (dark grey) to FT (light gray) conditions.

4.0 Discussion

The purpose of this study was to quantify the effects of aquatics sport expertise on neck/shoulder neuromuscular patterns during a repetitive, fatiguing upper limb task. We hypothesized that both water polo and swimming expert groups would perform the fatiguing task longer before reaching the fatigue criteria compared to the controls, however swimmers would last the longest out of the three groups. We also hypothesized that fatigue would be associated with increases in RMS, CoV, and NMI as well as decreases in MdPF amongst the various neck/shoulder muscles and muscle pairs. Further, we hypothesized that RMS would be higher and MdPF, CoV, and NMI would be lower in controls compared to both expert groups with swimmers having lower RMS and CoV, as well as higher MdPF and NMI than water polo players.

4.1 Effects of Aquatic Sport-Expertise on Performance and Muscle Activity Characteristics

IRFT time-to-fatigue was longest for the controls out of the three groups, with water polo players found to have significantly lower time-to-fatigue compared to controls, which disproves our hypothesis. A likely explanation for this observation is that the water polo players had significantly higher IR peak torque values in their MVRCs than both the swimmers and controls, such that the fatiguing task was more intense for the water polo group. Athletes, especially water polo players who are accustomed to short bouts of high intensity efforts, have more experience recruiting and controlling their shoulder muscles for intense, short burst efforts such as that performed in our pre-fatigue task. Thus, it is possible that both expert groups were more able to give a true maximal effort in their MVRC compared to the controls. As a consequence, the IRFT, adjusted to each individual's 50% MVRC, was likely closer to the experts' true capabilities and thus more fatiguing for the experts and even more so for the water polo players, compared to the control group. In addition, the significant differences found between water polo players and the other groups may be explained by differences in muscle activity characteristics amongst the groups. Fast-twitch type 2 muscle fibers are used to produce bursts of power such as sprinting, which is characteristic of water polo. Water polo players may have been able to produce a significantly higher peak IR torque due to having more type 2 fibers, which in turn made their 50% MVRC in the IRFT more difficult to sustain. Lastly, type 2 fibers have the least endurance and fatigue more quickly, adding another explanation for why water polo players may have had the shortest time-to-fatigue.

Finally, one last interpretation relates to the concept of the Borg scale. One of our fatiguing task termination criteria was for the subject to report 8 out of 10 on the Borg CR10 scale, corresponding to a rating of "Hard". It is possible that athletes are more used to experiencing high-intensity efforts and are thus more inclined to voluntarily rate an effort as hard, compared to novices. This then causes them to reach the stoppage criteria sooner than the controls, thus ending the task, when they likely could have maintained the effort for a much longer duration before truly being fatigued. However, since little support can be found in the literature for this interpretation, other studies, such as one which we are currently conducting in parallel, are necessary to compare the associations of Borg CR10 ratings to arm function and muscle activity.

4.2 Time Effects on EMG Characteristics

It is well-known that muscle fatigue leads to a decrease in MdPF in all kinds of tasks including repetitive, dynamic tasks, possibly due to a decrease in muscle fiber conduction velocity[12]. In addition, an increase in surface EMG amplitude in submaximal repetitive tasks has been interpreted as being reflective of possible increased recruitment of motor units in response to fatigue invoked by sub-maximal efforts where sub-maximal task termination criteria are used (as in our study)[10]. The specific role played by a given muscle in a task also has an impact on how the fatiguing task affects that muscle's EMG characteristics. Our results showed that there were decreases in MdPF for all muscles investigated, whereas there were increases in RMS for the PEC and AD. Results suggest that the PEC and AD likely acted as the main agonists to the IRFT whereas the LAT, IS, PD, MT, SS, and SUB could have acted as synergists and thus compensated in increasing their activity for fatigue induced in the main agonists.

Further, past research has identified increased variability as a sign of overall fatigue. The increase suggests that a re-organization of motor strategies occurs to slow development of muscle fatigue, relieve the load on fatiguing tissues, and attempt to preserve performance[14-16,57,82]. In our study, CoV increased with time in the AD, PD, UT, and LAT. This supports the hypothesis of increased variability with fatigue, in our case in both agonists and synergists, although the PEC, the main task agonist, did not show increased variability. This could be interpreted as a limit in the ability of this muscle to vary its behavior given the highly-constrained task. Indeed, past research showing increased variability with fatigue investigated tasks during which posture and movement could be slightly adjusted to take advantage of the available degrees of freedom to contribute to the task[53,56,57,60-62]. In comparison, our task, and especially as it regards the role of the PEC, provided little possibility to adjust shoulder posture and movement characteristics. In these constrained cases, motor variability would instead be taken advantage of by muscles playing a secondary role in contributing to the task, as our results suggest.

Lastly, functional connectivity for 23 out of 27 of the selected muscle pairs analyzed exhibited an increase with time. NMI increase has also been proposed as a sign of fatigue in submaximal, isometric tasks in past research[17,19,72]. Higher connectivity has also been interpreted as a search to share the load with another muscle or to maintain stability between neighboring muscle joints order to continue the task as fatigue develops[17,19]. Although the IRFT is not an isometric task, the constrained nature could be causing similar fatigue adaptations and our results are consistent with past research. They imply that the IRFT was successful in inducing acute muscular fatigue in the internal rotators, which in turn may seek to create new synergies with external rotators and scapular stabilizing muscles to compensate for fatigue[17,72]. In addition, as fatigue develops, the increased connectivity may be representative of an adaptation strategy to maintain stability within the shoulder joint.

4.3 Effects of Aquatic Sport-Expertise on Individual Muscles' Response to Fatigue

Past research suggests that experience contributes to neuromuscular synchronization, requiring less muscular activity compared with amateurs when accomplishing the same task[83]. Our results support this hypothesis, as in our study, the controls used more PEC, PD, and SUB throughout the conditions of the task. To note, there were no significant differences in RMS or MdPF between swimmers and water polo players, indicating that regarding amplitude and frequency, both expert groups used similar fatigue adaptations. Past research has shown that the SUB is highly activated in all phases of throwing and swimming due to acting both as a prime internal rotator and scapular stabilizer[84]. In addition, in the propulsive phase of various swimming strokes, the PEC is one of the most activated muscles, for the longest duration[85]. Therefore, water polo players are very accustomed to using their SUB and swimmers their PEC, and likely require less ongoing adjustments as fatigue develops in the activity of these muscles to complete the task. It makes sense to interpret that over the entire task, controls needed to initially recruit more SUB motor units and ended with a SUB that was more fatigued at the end of the task in comparison to water polo players. Regarding the PEC, we can infer that controls were likely favoring the AD and/or SUB to initially drive internal rotation. However, as the task progressed, they started to increase PEC engagement, which ended in the PEC being more fatigued compared to swimmers at the end of the task. Lastly, in the IRFT, the PD functions as an external rotator, which works to help decelerate the arm through the concentric internal rotation push. It is possible that due to controls being unaccustomed to using their PD in that specific manner, for controls to regulate the deceleration associated to this task, increased activation of the PD is required for the first half of the IRFT.

Past research suggests that experience/expertise in performing specific tasks or movements can influence motor variability[14-16,63]. In the IRFT, the AD is a prime internal rotator which works as an agonist and the UT is a scapular stabilizer which works as a synergist to elevate the humerus and scapula. Swimmers are trained to be more repeatable with their movements and to keep their strokes consistent. To add to this, past research has found that in top level swimmers' stroke and trajectory, EMG RMS and variability patterns were maintained and not easily changed with fatigue[86-91], thus helping to explain the lower AD and UT variability in swimmers compared to the controls. Higher UT variability in water polo players could possibly be linked to the fact that water polo players vary between swimming head down and head up (where the UT is more activated) and engage in overall more variable movement patterns in their sport[83,91]. Interestingly, there we no significant group differences in variability with fatigue, which suggests that due to the constrained nature of the task, fatigue adaptations could have involved more changes in muscle pair functional connectivity rather than individual muscle variability.

4.4 Effects of Aquatic Sport-Expertise on Between-Muscles' Response to Fatigue

We quantified NMI between internal rotators in order to study synergistic patterns, whereas NMI between rotators and stabilizers helps to understand coordination between scapular posture and glenohumeral muscle action. Past research on NMI differences seen with fatigue, gender, injury, and/or task type is contradictory, with higher functional connectivity seen in women[18,57] and isometric tasks[19,72] and lower functional connectivity in dynamic tasks[17,76] and injured individuals[77,78.]

Our results showed that the PEC was fatiguing more in controls relative to swimmers as described in section 4.3. This is further confirmed through our results that found that controls displayed higher functional connectivity which included the PEC as one of the muscle pairs compared to swimmers in the second half of the task. It is possible that due to the fatigue induced in the PEC, controls needed to share the load with another internal rotator (LAT) and two scapular stabilizers (SS and MT) to alleviate fatigue and continue to perform they task. This is in line with past research, which has shown that higher functional connectivity in controls and athletes performing an isometric task may be linked to a strategy to maintain stability between joints in order to maintain endurance[19,72]. Although the IRFT is not an isometric task, due to the constrained nature, it is plausible that similar fatigue adaptations occurred in our study. Moreover, water polo players seem to engage the UT and LAT with other muscle pairs more than the other two groups in the second half of the task. Due to the open and unpredictable nature of their sport, it seems that water polo players are more inclined to share the load between more muscles. Specifically, they appear to adapt a strategy to synchronize a bigger number of agonist shoulder muscles (LAT, SUB and PEC). Further, their adaptation strategy seems to involve engagement of a wider range of synergies involving the LAT and AD as internal rotators and the trapezius as scapular stabilizers. Lastly, compared to water polo players and controls, swimmers showed lower functional connectivity in all significant muscles pairs. It could be interpreted that swimmers are more repeatable in their muscle coordination patterns and this leads to an adaptation strategy to isolate muscle fatigue to prevent spread. Our results are similar to those described in two studies which compared functional connectivity in men and women performing a repetitive submaximal pointing task[17] and repetitive box-folding task[18]. Both studies found higher functional connectivity in women compared to men and suggested that it could be considered to be a suboptimal strategy and could represent co-contraction that could increase the risk of injury development, which is much more frequently observed in women compared to men[17,18]. It is difficult to comment on whether these results could speak to simply being an indicator of differing fatigue strategies in different populations or represent a good or poor strategy towards injury development.

Limitations

There are a few limitations that exist in relation to this study. When observing surface EMG data of the shoulder during a dynamic task there is the possibility of the electrodes recording data from neighboring muscles, although this limitation is reduced in the three muscles that we investigated using intramuscular electrodes. Also, some participants may not have given a true maximal effort in their MVRCs, possibly making the task less demanding than 50%. Finally, results are not generalizable to the entire population, as participants only included healthy, young, female volunteers recruited through university and national sport networks.

Conclusions

The present study investigated the effects of expertise on neck/shoulder neuromuscular patterns during a repetitive fatiguing upper limb task. Controls were characterized by higher pectoralis major, subscapularis, and posterior deltoid muscle activity, higher anterior deltoid and upper trapezius variability, and higher functional connectivity involving the pectoralis as a muscle pair. These characteristics point to both the pectoralis major and subscapularis being more fatigued in the controls, compared to the experts at the end of the task. In order to prevent injury, it may be beneficial for individuals joining a swimming or water polo team to focus on an intervention program which targets these muscles. Water polo players were characterized by lower subscapularis activity, lower anterior deltoid and higher upper trapezius variability, and higher functional connectivity involving the latissimus dorsi and upper trapezius. Swimmers were characterized by lower pectoralis activity, lower anterior deltoid and upper trapezius variability, and lower functional connectivity. It is unsure if the experts' respective fatigue adaptation strategies, with the swimmers remaining more repeatable, and the water polo players more variable, are beneficial or detrimental. The two sports, although similar, are also very different. Future studies focusing on injured versus non-injured expert athletes are need to gain a better understanding of the implications on the differing strategies. This study contributes to the growing literature around repetitive movements and fatigue adaption strategies. Findings may help identify mechanism-based interventions to reduce or prevent neck/shoulder injuries in sports populations.

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CONCLUSION

Results from this study further contribute to the existing literature on submaximal, repetitive motion induced fatigue and to literature on expert differences in response to localized muscle fatigue. To our knowledge, this is one of the first studies to compare upper limb EMG neuromuscular adaptation patterns (amplitude, frequency, variability, and functional connectivity) induced by fatigue between a control group and two expert aquatic overhead athlete groups. Our results suggest there are expert and time differences in the recruitment and utilization of shoulder internal rotators and scapular stabilizers. However, the results from this study may only be applied to healthy, female populations, therefore more research is required to further understand the effects of expertise on fatigue adaption strategies. Ideally, future research will focus on differences in other populations such as males, injured, or other types of overhead athletes, etc. It would be interesting to confirm whether past research in ergonomics that shows that men have less variability and functional connectivity compared to women and same with injured individuals showing less compared to healthy individuals is upheld in sports research. Further, our athlete population consisted of young adults. Past research suggests that as we age, our neuromuscular system becomes less adaptable. This knowledge could be expanded if we study individuals who have been upper limb athletes their entire life, to understand how that training may have affected their aging process. Lastly, a notable difference in strategies was seen between the swimmers and water polo players, which we partly attributed to the open or repeatable nature of each sport. Going forward, research should compare for example, swimmers to karate athletes, where consistency is also valued. This would give more information regarding whether a specific type of upper limb training affects the fatigue response in different ways. In summary, this study adds to the current body of literature on repetitive fatigue adaptions, with the goal to identify mechanism-based interventions to reduce or even prevent neck/shoulder injuries in sports populations. This and future research will help to gain a more complete understanding of motor adaptations in response to fatigue and how it is affected by expertise, gender, injury, etc. In turn, this new knowledge can help better understand how training affects the neuromuscular system, to optimize training approaches and better prevent injuries.

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APPENDICIES

Appendix 1. Consent Form (English)

CRIR Centre de recherche interdisciplinaire en réadaptation du Montréal métropolitain

Consent form

Centre intégré de santé et de services sociaux de Laval Québec

1 - Title of project

Effects of shoulder fatigue on muscular patterns and performance in female 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.

Savannah King, B.Sc., Master's student, Department of Kinesiology and Physical Education, McGill University, (514) 398-4455 ext. 0583, (450) 688-9550, ext. 4827.

Michelle Caron, B.Sc., Master's student, Department of Kinesiology and Physical Education, McGill University, (514) 398-4455 ext. 0583, (450) 688-9550, ext. 4827.

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 of women in aquatics sports, affects the fatigue response. Forty-five healthy teens and adults: 15 swimmers, 15 water polo players, and 15 controls will be recruited to complete this study. The long-term objectives of this research are to better understand how a person responds to muscular fatigue, which can lead to 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 and a tight fitting tank top. ***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.

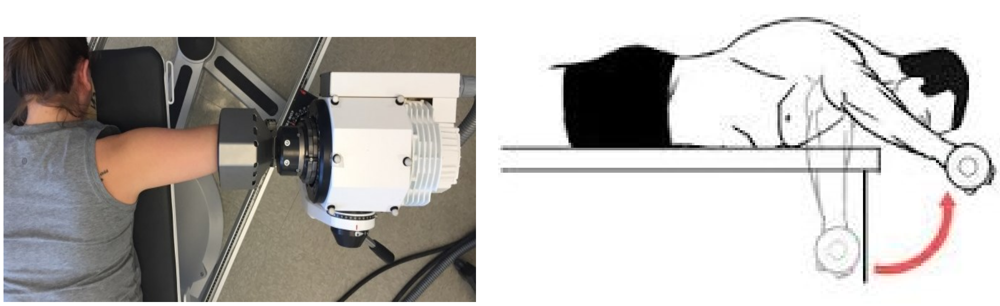

Figure 1 : experimental setup, fatiguing task

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 Savannah King at savannah.king@mail.mcgill.ca or Michelle Caron at michelle.caron4@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.

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_____.

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_____.

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 2. Formulaire de consentement (Consent Form - French)

CRIR 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 femmes expertes 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.

Savannah King, 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.

Michelle Caron, 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 des femmes dans les sports aquatiques, affecte la réponse à la fatigue. Quarante-cinq adolescentes ou adultes en bonne santé : 15 nageuses, 15 joueuses de water-polo, et 15 participantes contrôle, seront recrutées pour participer à cette étude. Les objectifs à long terme de cette recherche sont de mieux comprendre comment une personne répond 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 et une camisole ajustée à la peau. ***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.

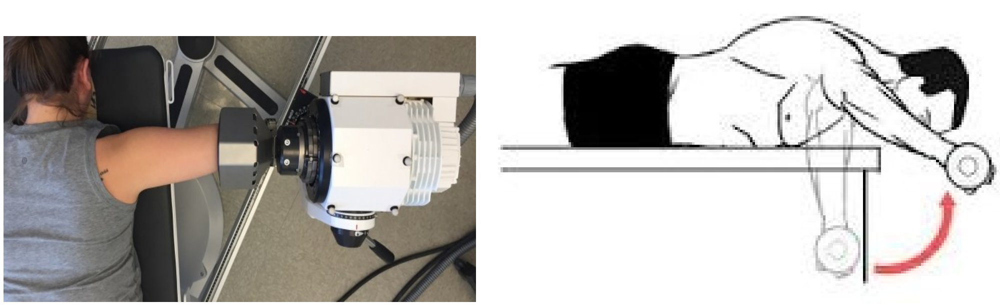

Figure 1 : montage expérimental, tâche de fatigue

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 Savannah King au savannah.king@mail.mcgill.ca ou Michelle Caron au michelle.caron4@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.

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_____

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____ ».

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 3. 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 4. Modified Borg CR10 Scale (French)

Note	Description
0	Rien du tout
0.5	Trés, trés faible
1	Trés faible
2	Faible
3	Modéré
4	Plutôt fort
5	Fort
6	
7	Trés fort
8	
9	
10	Maximale