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Defining the relationship between encumbered ensembles and task performance in diving operations

A pilot study

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Abstract

DRDC's Experimental Diving and Undersea Group (EDU) recognizes the requirement for a capability to perform sound human factors and ergonomic research to support the specification, design, development, and evaluation of diving clothing, equipment and platforms. In order to leverage the emerging tools and capabilities available through DRDC's Comprehensive Ergonomics-based Tools and Techniques (CETTs) capabilities, a pilot study was conducted to evaluate the effect of ensemble encumbrance on diver underwater task performance.

Five Royal Canadian Navy Reserve divers were recruited from the HMCS York to participate in this study. Each diver participated in three dive encumbrance conditions consisting of either a a) 6mm thick wetsuit, b) Fusion dry suit or c) Kodiak dry suit. An AGA full face dive mask and Compressed Air Breathing Apparatus (CABA) tanks were worn in each condition. Dive ensemble encumbrance was quantified by obtaining 3D volumetric scans, and measuring field of view and cervical range of motion. In-water assessment of ensemble encumbrance consisted of whole-body range of motion activities.

Performance tasks were based on simulated mine counter measures tasks and consisted of fine motor (rope tying and nuts/bolts assembly), gross motor (weight transfer) and a visual search tasks. All in-water tasks were recorded using waterproof GoPro™ cameras and evaluated according to time to task completion, NASA TLX response and subjective questionnaire. Despite the low number of participants, results indicated trends that were consistent with task performance being adversely affected by encumbrance, as defined by a reduced range of motion. The exception was the nuts and bolts task which appeared to benefit by the extra stability provided by a more restrictive suit. This research reinforces the importance of identifying objective measures of encumbrance that are relevant to diver task performance. Challenges to quantifying dive ensemble encumbrance in an underwater environment are identified and research gaps, tools, resources and facilities to support advanced diving human factors research are identified.

Significance for defence and security

This report describes the results of a pilot study to apply novel ergonomics-based tools, equipment and methods to evaluate the underwater performance of divers performing simulated mine-counter measures tasks. The results of this study can be used to inform future human factors and physical ergonomics research to support the specification, design, development and evaluation of clothing, equipment and platforms used in diving operations. Additional recommendations are made to identify research gaps, tools, resources and facilities to support advanced diving human factors research.

Résumé

Le Groupe de l'unité de plongée expérimentale (GPE) de RDDC reconnaît la nécessité de posséder la capacité d'effectuer des recherches approfondies sur les facteurs humains et l'ergonomie pour appuyer la description, la conception, la mise au point et l'évaluation des vêtements, de l'équipement et des plateformes de plongée. Afin de tirer profit des capacités et des outils émergents qu'offre l'ensemble exhaustif d'outils et de techniques ergonomiques (EEOTE) de RDDC, on a mené une étude pilote dans le but d'évaluer l'effet de la charge exercée par l'équipement sur l'efficacité des tâches effectuées sous l'eau par les plongeurs

On a recruté cinq plongeurs de la Marine royale canadienne (Réserve) parmi l'équipage du NCSM York pour participer à l'étude. Chaque plongeur a pris part à trois exercices selon différentes charges de plongée, à savoir : a) une combinaison humide de 6 mm ; b) une combinaison étanche Fusion ; c) une combinaison étanche Kodiak. Tous les plongeurs étaient équipés d'un masque facial intégral AGA et des bouteilles de plongée d'un appareil respiratoire à air comprimé (ARAC) lors de chaque exercice. La charge selon l'équipement de plongée a été quantifiée au moyen de balayages volumétriques et en mesurant le champ visuel et l'amplitude de mouvement cervical. L'évaluation sous l'eau comportait des exercices de mouvement d'amplitude de tout le corps.

L'exécution des tâches consistait en une simulation d'exercices de lutte contre les mines et comportait des activités de motricité fine (nouage de cordes et assemblage par boulons et écrous), de motricité globale (transfert du poids) et de recherche visuelle. Toutes les tâches sous l'eau ont été enregistrées au moyen de caméras étanches GoPro^{TM} et évaluées en fonction du délai pour les mener à bien, de l'indice de charge de travail (ICT) de la NASA et d'un questionnaire subjectif. Malgré le nombre peu élevé de participants, les résultats ont montré des tendances qui correspondaient à l'efficacité des tâches sur lesquelles la charge exerce une influence défavorable, comme l'indique une amplitude de mouvement réduite. L'exception étant l'assemblage par boulons et écrous, celui-ci a semblé profiter d'une plus grande stabilité qu'apportait une combinaison plus contraignante. L'étude confirme l'importance d'établir des mesures objectives pour évaluer la charge pouvant avoir une incidence sur l'efficacité du travail des plongeurs. On a souligné la difficulté de déterminer la charge globale de l'équipement de plongée dans un environnement sous-marin, ainsi que les lacunes sur le plan de la recherche, des outils, des ressources et des installations pour appuyer des recherches approfondies sur les facteurs humains relatifs à la plongée.

Importance pour la défense et la sécurité

Le présent rapport contient les résultats d'une étude pilote dans laquelle on utilise de l'équipement, des méthodes et des outils ergonomiques novateurs afin de mesurer l'efficacité des plongeurs qui procèdent à une simulation des tâches relatives à la lutte contre les mines. Les résultats de cette étude permettront de fournir des renseignements sur les facteurs humains futurs et la recherche en ergonomie physique pour appuyer la description, la concep-

tion, la mise au point et l’évaluation des vêtements, de l’équipement et des plateformes de plongée. On énonce des recommandations supplémentaires dans le but de déterminer les lacunes en matière de recherche, d’outils, de ressources et d’installations pour appuyer des recherches approfondies sur les facteurs humains relatifs à la plongée.

Table of contents

List of figures

List of tables

Acknowledgements

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1 Introduction

1.1 Background

Diving is an imperative role in the Royal Canadian Navy (RCN) and is comprised of specialized tasks and missions. Such missions include Mine Counter Measures (MCM), Explosive Ordnance Disposal (EOD), Battle Damage Repair (BDR), Force Protection Support (FP Support) and Under Water Engineering. There are currently a lack of objective tools and methods to inform the procurement of dive ensembles the Canadian Armed Force (CAF) diving community. To support the requirement for the development of an objective framework to guide the development and validation of requirements of CAF diving equipment, a Human Factors Program Plan (HFPP) for the CAF diving program has been developed (Angel and Tack, 2015). Along with the development of the complementary Human Factors Test Plan (Angel and Tack, 2015), DRDC and the Experimental Diving Undersea Group have sound guidance on the implementation of Human Factors principles in all aspects of system design and acquisition.

Working in an immersed environment imposes a number of inhibiting factors that can have an impact on task performance. Environmental factors may include: depth, visibility, buoyancy, turbulence, drag force, and water temperatures (Baddeley, 1966; Bachrach & Egstrom,1974; Hancock & Miller, 1986; Arieli et. al, 1997; Zander & Morisson, 2008; Hoffmann & Chan, 2012). Since these circumstances may often be beyond the diver's control, certain precautionary measures must be accounted for to warrant the safety and success of the mission. Despite adequate skill levels and physical conditioning needed for the safety and success of a mission, the dive garments and equipment may provide an impediment to this objective. Material characteristics such as the weight, thickness, stiffness, buoyancy and friction can contribute to a decrease in performance (Adams & Keyserling, 1995; Huck, 1988; Uglene et. al, 1998). Of those factors, the bulk and configuration of the ensembles impose encumbrance to the diver and can lead to a greater decrease in task performance (Huck, 1988; Uglene et. al, 1998; Son et. al, 2010).

While personal protective equipment (PPE) is meant to protect the worker from their work environment (Adams, et al., 1994) a decrement in task performance may be attributed to the PPE's effect on the worker's range of motion (ROM). Range of motion is defined as the maximum angular change at a joint, measured in degrees from a reference point (Chaffin et. al, 1984). A reduced ROM appears to be a consequence of wearing PPE (Adams and Keyserling, 1993; Adams, et al., 1994; Adams & Keyserling, 1995; Coca et. al, 2010; Margerum et. al, 2012). This is exemplified by a 1987 survey of Canadian military and commercial helicopter pilots. It revealed that 72% of the military and 86% of the commercial pilots found their survival suit to restrict movement (Gaul & Mekjavic, 1987).

Mobility, dexterity, and comfort are inherently traded off for protection (Bachrach, Egstrom & Blackmun, 1975; Banks 1979; Zander & Morisson, 2008). By excessively compromising performance, the divers safety could be at risk; that is, if an emergency arises, a cumbersome ensemble could impede the divers ability to escape the hazardous environment since ROM, movement speed, and accuracy are reduced, and exertion is increased (Adams, Slocum, & Keyserling,1994; Adams & Keyserling, 1995).

Field of view (FOV) also plays a role in task performance limitations, since dive masks can obstruct peripheral vision. A restricted FOV can decrease the velocity and accuracy of movement and affect overall task performance (González-Alvarez et. al, 2007; Toet et. al, 2007). Large head and whole body movements are required to compensate and orient individuals with a limited FOV (Alfano & Michel, 1990). Although, these compensatory movements may be difficult to carry out while wearing a restricting ensemble, a less impeding garment could save on labour and physiological costs as productivity would increase (Adams et al., 1994). Unfortunately, the quantitative relationship between ensemble encumbrance and task performance is poorly understood. By quantifying and parameterizing encumbrance and its functional restrictions, manufacturers would be able to develop PPE that could better accommodate the safety and efficiency of the worker (Adams & Keyserling, 1993).

1.2 Purpose of the study

The purpose of this pilot study is to evaluate and apply ergonomics-based tools and methodologies available through the Comprehensive Ergonomics-based Tools and Techniques (CETTs) capability to aid in the development of a standardized methodology to evaluate dive ensembles and equipment by assessing diver performance in above and underwater tasks. Relevant CETTs capabilities include 3D whole-body laser scanning, and optical and video-based motion analysis. It is hypothesized that ensemble encumbrance, depicted from ROM and 3D scanning measurements, will be positively correlated with decreased mobility and fine and gross motor task performance.

2 Methods

2.1 Participants

Royal Canadian Navy Reserve Divers from the HMCS York Naval Unit were recruited to participate in this pilot study. Participants were informed that this study had received DRDC Human Research Ethics Committee approval and were briefed on its purpose, risks and benefits of this study. They were provided with a copy of the Participants Information sheet (Annex A) to provide them with an overview of the study. The inclusion criteria were as follows: qualified Canadian Armed Forces (CAF) divers, hold current qualifications and were deemed proficient and medically fit to dive, male or female, between the ages of 18–60 years. All participants were briefed as to the purpose, risks and benefits of the study by the Principal Investigator and signed the Informed Consent form. Volunteers were informed of their right to withdraw from the trial at any time.

2.2 Location

All experimental trials were conducted at DRDC Toronto Research Centre. Dry land activities were held in the CETTs laboratory, while in-water diving activities were held in the Experimental Diving and Undersea Group (EDUG) static tank (Figure 1). The EDUG static tank is a water filled 8' x 8' x 10' facility maintained at a temperature of approximately 21°C. A viewing window built into one of the tanks walls allowed for viewing of all underwater activities. An underwater speaker system allowed for instruction to be communicated to the divers from the experimenters and dive master above.

Figure 1: *EDUG static dive tank.*

2.3 Suit conditions

Three diving suits were evaluated as part of the this study. Two dry suits, Kodiak (360 Drysuit, Whites Manufacturing, BC) and Fusion (Tactical MCM Drysuit, Whites Manufacturing, BC) were designated as the encumbered conditions (Figure 2). The Kodiak dry suit is made up of supplex multi-laminate fabric. It can be measured and custom fitted to an individual. The Fusion dry suit is made up of Supplex® multi-laminate Denier bi-laminated fabric and is available in 5 different stock sizes to fit a range of sizes. A thin undergarment was worn underneath each of these garments to improve comfort and thermal protection. A standard wet suit (Brooks Dive Gear, BC) (Figure 2) served as the reference condition as it was deemed to be the least bulky suit. The wetsuit is comprised of 6mm polyethylene throughout the suit, with the exception of 4mm at the back of the knees. Each diver performed a sequence of above and underwater tasks in each of the three suit conditions. The order of suits worn by each diver was randomized and counterbalanced to minimize potential effects due to learning or fatigue. Each diver also wore 3 mm thick, 5-finger neoprene gloves that had titanium-slick-skin lined palms (Whites, BC) (Figure 3). An AGA mask (Aqua Lung, CA) (Figure 4) and Compressed Air Breathing Apparatus (CABA) (Figure 5) was used during the in-water tasks.

Figure 2: *Suit conditions- Kodiak (left) , Fusion (middle), wetsuit (right). Retrieved from* `https://www.whitesdiving.com/military/`*. Reprinted with permission from Harald Knippelberg, 11 September 2017.*

Figure 3: *Five-finger neoprene gloves back (left), left (right).*

Figure 4: *AGA dive mask.*

Figure 5: *CABA dive tanks.*

2.4 Participant Characteristics

2.4.1 Anthropometry (body size)

A total of four measures were manually collected for each participant using anthropometric instruments such as calipers and a measuring tape. The measures were obtained for the purposes of characterizing each participant.

Measures taken include:

1. Stature;
2. Weight;
3. Chest circumference; and
4. Waist circumference.

2.4.2 3D scanning

Participants underwent a 3D scanning process, similar to that described by Jones et. al., (2013). This methodology describes scanning participants in semi-nude and encumbered conditions and in multiple postures. For this study, 3D scans were obtained in each of the Fusion, Kodiak, and wetsuit conditions. In order to provide additional utility for future analysis, and additional identification and marking of 26 anatomical landmarks (Figure 6) was included in this study.

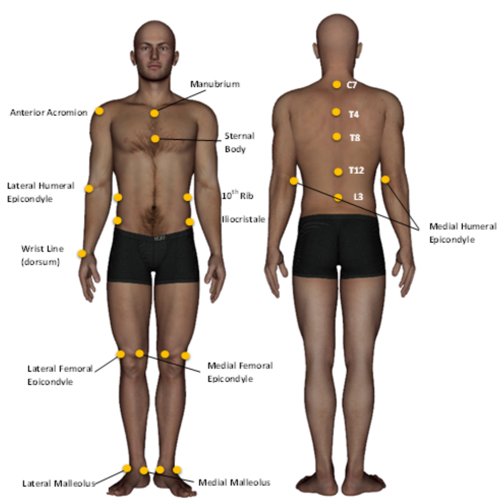

Figure 6: *Landmark locations for semi-nude 3D scans.*

Following the method developed in the 2012 Canadian Forces Anthropometric Survey (Keefe et al., 2015), participants were provided with a private change area where they undressed to the level of their underwear and don compression (unpadded bicycle) shorts and a sports bra (for women). Land marking was done in a private area where a measurement team member then marked anatomical reference points on their body by drawing a small cross "+" with a hypoallergenic eyeliner pencil. The measurement team member identified the landmarks by sight, palpation and movement. The measurement team included members of each sex, and on request, measurements were taken by an observer of the same sex. To enhance the contrast of the landmark for post scan identification, a self-adhesive, 12 mm high contrast roundels was placed each landmark (Figure 7).

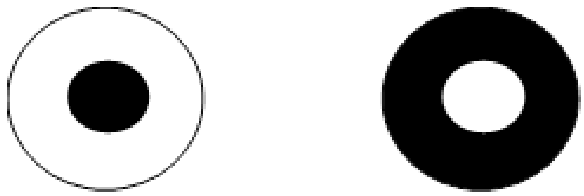

Figure 7: *3D scanner roundels used for landmark identification.*

Three-dimensional body scans were obtained in a standing posture using the the VITUS XXL laser scanning system (Human Solutions of North America, Cary, NC) (Figure 8). This system includes 4 laser scanning columns bolted into an aluminum frame, a personal computer with a monitor, and an analog to a digital signal converter box. A laser sensor moved linearly along the participant, from top to bottom, to record the scan image. Immediately after scanning, a visual check of the scan for completeness, moving artefacts, or incorrect posture was completed. Anthroscan v3.05 software (Human Solutions of North America, Cary, NC) was used to process the 3D images, stitch the multiple images together, correct scan anomalies and extract dimensions captured by the VITUS XXL whole body scanner.

Figure 8: *VITUS XXL laser scanning system.*

2.4.3 Scan Postures

Four standing scan postures (Figure 9) were taken for each participant in the semi-nude as well as each of the three suit conditions. Four postures were required to gather sufficient data to account for occlusions or voids in the scan and to account for shifts in the clothing ensemble with posture. Each scan took approximately 12 seconds to complete. To support the load of the CABA tanks and ensure a consistent and still scan posture, an supporting stand was fabricated and adjusted for the height of each participant.

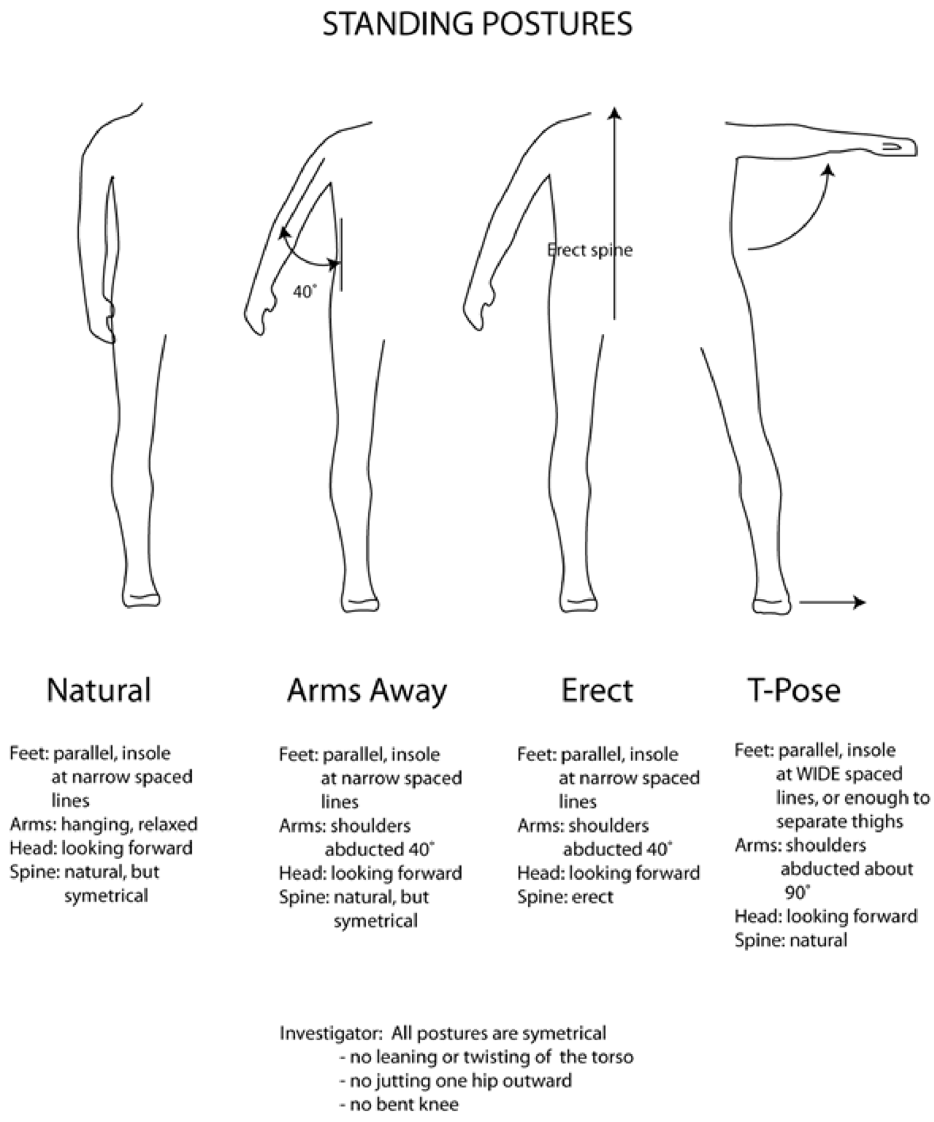

Figure 9: *3D standing scan postures.*

2.4.4 Range of motion

2.4.4.1 Warm up

Prior to each ROM assessment, participants were instructed to perform a standardized warm-up stretching routine as described by Gerhardt et al., (2002) to enhance performance and reduce their risk of injury. This warm-up included a brief period of a sub-maximal aerobic warm-up activity and a bout of static stretching. The researcher-led dynamic warm-up included the following components:

- **Bent Over Rotations:** Begin with feet at a comfortable stance wider than shoulder width. Bend over at hips with arms fully extended at sides at 90 degrees from torso. Begin by swinging right arm towards left foot and repeating on opposite side. Continue this motion through comfortable range, but do not strain. Continue this motion for 30 seconds.

- **Arm Circles:** Stand with feet shoulder width apart and knees slightly bent. Raise arms to a 90 degree angle from the torso with arms fully extended. Begin by making small circles by bringing arms forward and gradually increase to a full range of shoulder motion. Change direction at 15 seconds. Repeat motion with arms moving in opposite direction for 15 seconds.

- **High Knee Hold:** Walking while raising knees to chest: once knee has reached highest point of ROM, pull knee till a slight stretch is felt, continue with movement. Continue motion for 30 seconds alternating legs during walking.

- **Lunge walk and trunk rotation:** Begin by taking a large step in a forward direction and lowering body until the forward knee is at 90 degrees. While at lowest position rotate upper body towards forward leg through full ROM until slight stretch is felt. Bring other leg forward and repeat on other side. Continue lunge walk for 30 seconds.

- **Leg swings (forward/backward):** Stand with side to the wall. Extend arm sideways for support and move one arm length away from the wall. With hand on the wall, raise the leg closest to wall off of ground and begin by swinging it fore and aft, through the full ROM without straining. Continue for 15 seconds on one leg. Rotate position and repeat on opposite leg for an additional 15 seconds.

2.4.4.2 Cervical Range of Motion

Cervical range of motion (CROM) was the only functional task evaluated on dry-land. The primary reason was that a pilot study revealed that, during in-water testing, markers placed on the head could not be tracked reliably in all planes of motion due to their close placement and resolution of the video recording. While it was preferred to conduct this evaluation in-water, it was decided to use a more precise, laboratory-based, optical tracking system. Conducting the CROM measures on dry-land also made it easier to isolate the neck movement from the compensating torso movements that naturally occurred during in-water test. As the hoods worn in each dive condition were form fitting, it was anticipated that the hydrostatic pressure experienced would have minimal impact on suit compression, unlike the body suits which were loose fitting in the Fusion and Kodiak conditions. Finally, dry-land evaluation of CROM allowed for an unencumbered test condition. This could not be done for the encumbered condition due to the temperature of the static tank was too cool for semi-nude immersion.

Three motion capture markers were placed on a headpiece to record cervical motions in the x, y, and z-axis with the use of the Qualisys optical motion capture system (Qualisys North America, Highland Park, Ill) (Figure 10). Range of motion data were collected for neck flexion/extension, lateral bending and axial rotation. Each exercise conducted in the semi-nude and all suit conditions. Suit conditions included the CABA tanks and AGA mask. Each motion was repeated twice and movements were captured at 60 frames per second, graphed, and recorded to the nearest degree.

Figure 10: *Cervical range of motion with the Qualisys optical motion capture system.*

2.4.5 Baseline field of view

A baseline, functional field of view measure of both the baseline (no mask) and mask conditions were recorded with the use of a perimeter device (Figure 11). An eye patch was worn by each participant so that the monocular visual field of view could be assessed for each eye. Participants were instructed to place their chin on the chinrest such that their eye was placed at the reference pole of a semi-circular perimeter device. The perimeter was marked with angular coordinates, and a green light-emitting diode (LED) was installed on a slider attached that could be placed at random coordinates along the bar. Once placed in position, the LED was illuminated by the investigator by pressing a remote button. With their head in a fixed position, the participant proceeded to visually scan the perimeter. Successful visual identification of the LED was recorded if the participant could see the point light emanating from the LED, rather than its glare. The placement of the LED was randomly adjusted to titrate the limits of the field of view . The limits to the field of view were recorded in degrees and the perimeter bar was re-adjusted at 0, 45 and 180 degrees to obtain measures for the left/right horizontal, diagonal, and up/down vertical arcs. Black screens surrounded the area to remove any background visual distractions to facilitate the identification of the LED target.

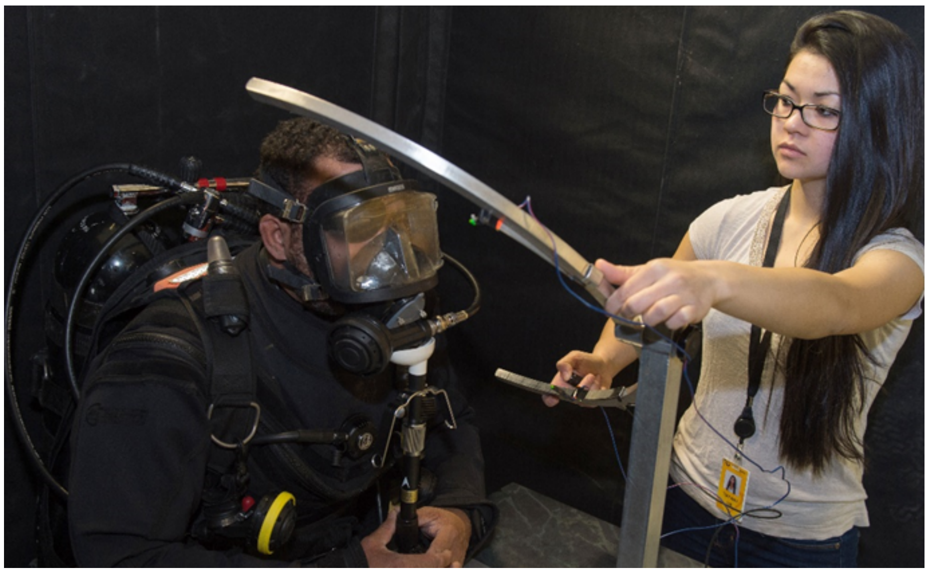

Figure 11: *Field of view measuring tool (Perimeter). The green LED is visible in the foreground arc of the perimeter.*

2.4.6 In-water performance-based tasks

During all in-water tasks, the divers were fully equipped wearing fins, a CABA air tank, AGA mask, 5-finger neoprene gloves, and weighted belts for each suit condition. Note that this differs from the in-water ROM test where ankle weights were worn instead of fins to maintain stability under water. All tasks were completed in approximately 1hr, for each experimental condition.

As water temperature could not be regulated above a room temperature of 20°C, a semi-nude condition could not be used to serve as a reference condition due to concerns of muscle and body cooling. As an alternate, the wetsuit condition was considered as the control as it was considered to be the less bulky of the three suit conditions. Unlike the CROM measures, an dry-land whole body ROM was not conducted as a buoyant environment was required to support the weight of the CABA tanks worn by the divers. Second, it was anticipated that buoyancy and hydrostatic forces would act on the suit, affecting performance. Thus, it was assumed that dry-land ROM would not be indicative of in-water ROM for these tasks.

All tasks were demonstrated to the participants on dry land, and they were provided an opportunity to practice the fine motor and Rope Tying tasks until it was determined by the participant and experimenter that they were familiar and proficient with the tasks.

2.4.6.1 Range of Motion

As buoyancy jeopardized postural stability, for this task only, the divers were equipped with ankle weights instead of swimming fins to assist with their stability

A set of 7 range of motion movements (Figure 12), adapted from Bachrach, Egstrom & Blackmun, (1975) were used as these movements have been previously justified by these authors for diving application. All ROM movements were encouraged to be completed to the participant's fullest extent. Each motion was performed twice to provide an average range of motion value.

Figure 12: *Anthropometric range of motion measures. Top row: shoulder abduction, hip flexion, trunk flexion. Bottom row: left trunk rotation, right trunk rotation.*

These movements were recorded underwater with the use of two waterproof, wide angle lens GoPro camera (GoPro, San Mateo, CA) placed above and to the front of the diver (Figure 13).

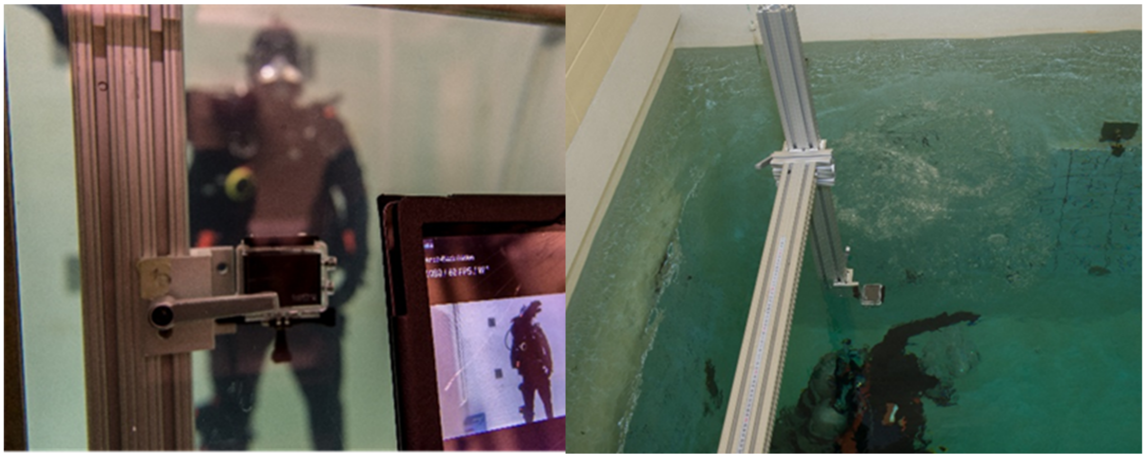

Figure 13: *Waterproof wide lens GoPro camera in-water placement. Front view (left,) overhead view (right).*

High colour-contrast (SOLAS orange) markers were affixed to the divers' torso, as well as upper and lower extremities to facilitate the identification and tracking of these landmarks (Figure 14). The 2D footage was used for kinematic analysis, specifically measuring changes of joint angles throughout the range of motions with the use of the video analysis software Kinovea v0.8.15 (Kinovea, France).

All ROM movements were demonstrated and practiced in an unencumbered (shorts, t-shirt) condition before entering the dive tank. The diver then donned their diving gear and entered the dive tank, where these movements were repeated. An underwater speaker/microphone system was used to communicate with the diver to guide them through the movements.

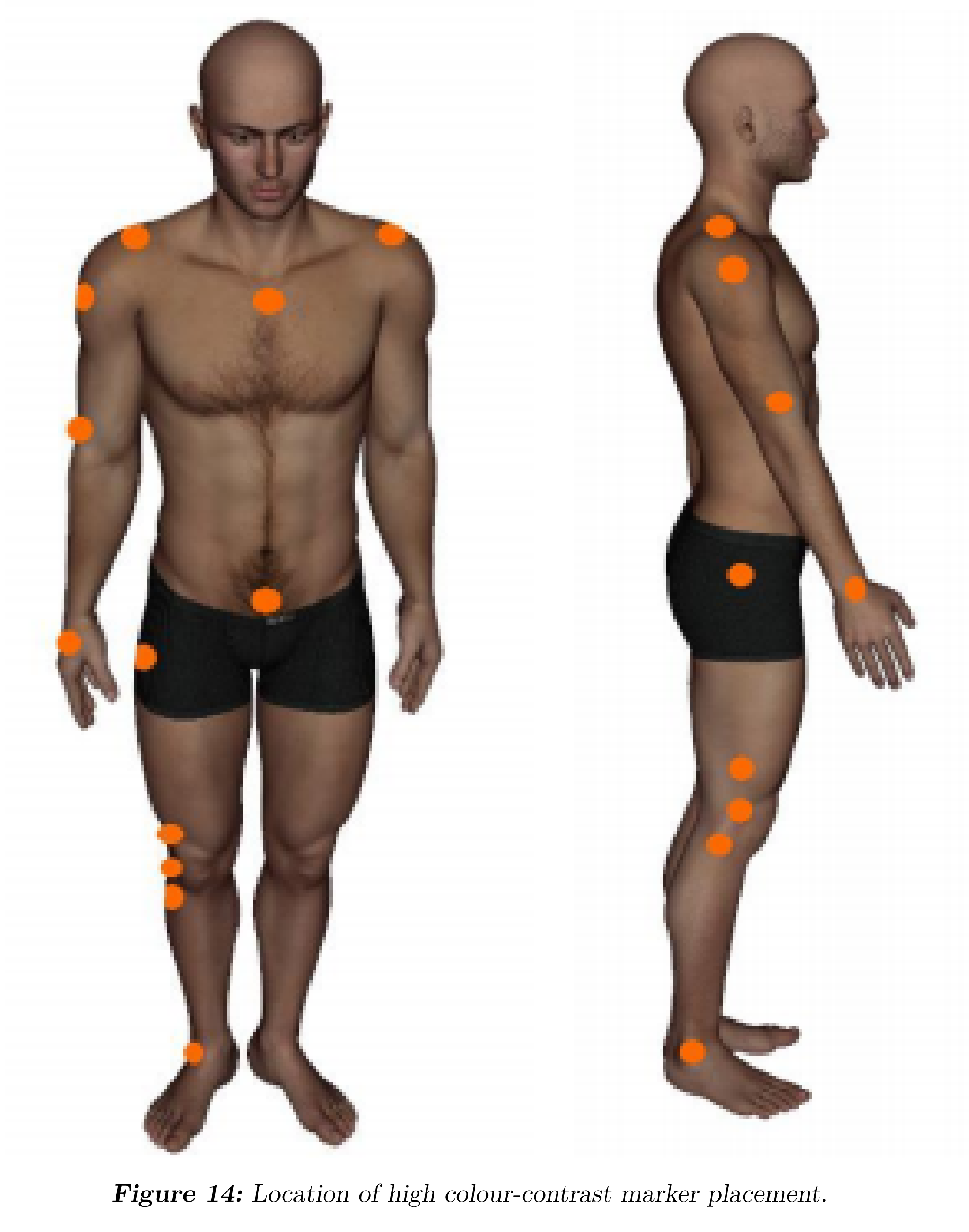

Figure 14: *Location of high colour-contrast marker placement.*

2.4.6.2 Fine motor task – Two-tiered horizontal bolt board

Participants entered the 8' x 8' X 10' static dive tank and positioned themselves at a central location on the tank floor. A custom stainless steel version of a two-tiered horizontal Nuts and Bolts task board was fixed to a wall located approximately 1m above the floor (Figure 15). The bolt board has 8 colour-coded bolts on the upper tier, arranged in descending diameter from left to right. Each of these bolts held two sets of nuts and washers arranged in alternating order. Each bolt size/colour combination on the upper tier was represented by two corresponding bolts on the lower tier. The objective of this task was to transfer a nut and washer pair from the upper tier to a corresponding, unused bolt on the lower tier. This done in an ordered manner, beginning with largest diameter bolt in the upper left tier and working rightward to the smallest diameter bolt. The nuts were required to be fully tightened allowing no movement of the washers. Task performance was scored as the total number of nut/washer pairs transferred within a 5 minute period. Removal of the gloves was not permitted, although, use of a working knife was permitted, if needed.

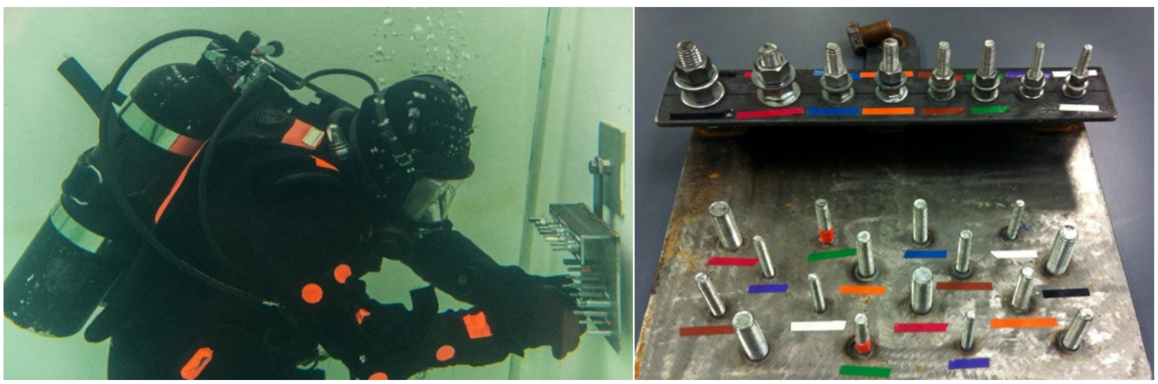

Figure 15: *The two tiered horizontal bolt board.*

2.4.6.3 Fine motor task – Rope Tying

The second fine motor task consisted of tying a bowline knot (Figure 16) followed by two half hitches around an anchor. They were required to immediately un-tie the knot afterwards. This was repeated for a total of three times. This task was timed, and the divers were encouraged to perform this task as quickly as they could.

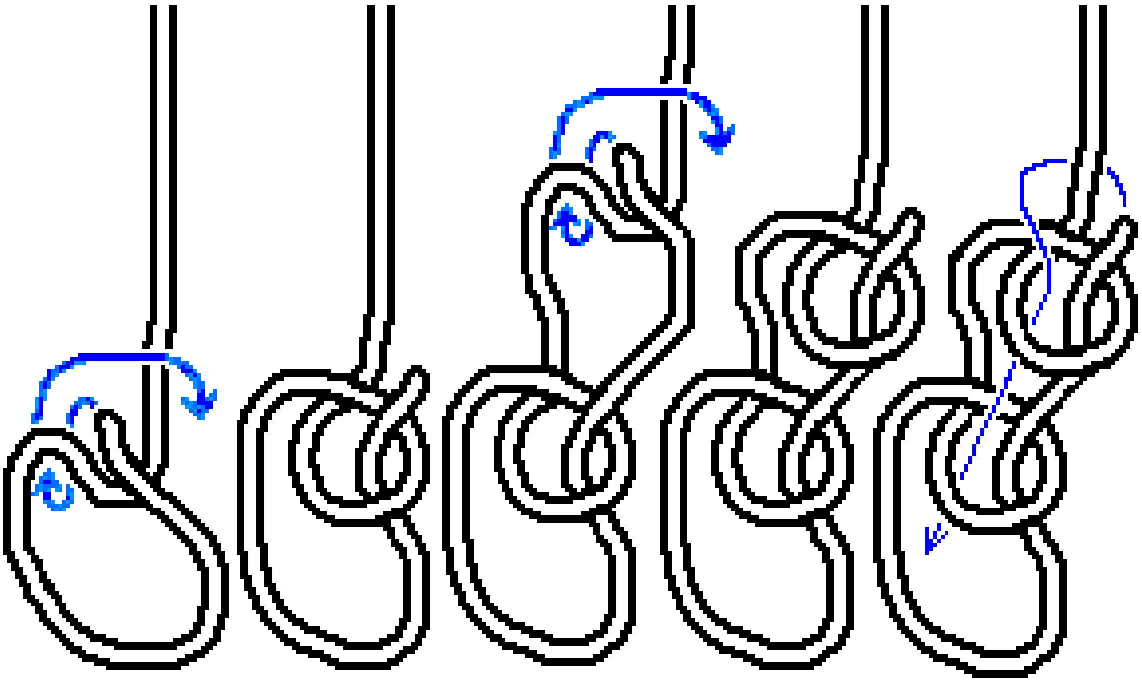

Figure 16: *Bowline with two half-hitch knot used for Rope Tying task.*

2.4.6.4 Gross motor task – Weight Transfer

The gross motor task was designed to simulate the transfer of debris or tools on a mission. Milk crates were secured in opposing corners of the static tank and a 4.5kg weight was transferred from one milk crate to the other as many times as possible within 5 minutes (Figure 17). Transfer techniques varied, but the diver was instructed to place the weight on the bottom of the milk crate. Throwing or dropping of the weights into the basket was not permitted.

Figure 17: *Gross motor weight transfer task.*

2.4.6.5 In-Water Field visual search task

Three grid boards of approximately 1m x 1.5m with a 6 x 5 grid of randomized numbers were fixed on the walls of the static tank (Figure 18). The experimenter would present the participant with a number through the observation window prompting the diver to scan and locate the shown number. Once the number was located, the diver was required to touch the identified number for confirmation. A total of 10 numbers were presented and the average time from presentation to identification was recorded. There were 3 configurations of grid boards, all of which were presented in a counterbalanced manner across participants to control for any learning effects. Grid boards were fixed to the walls at two different heights in order to increase the level of difficulty of this task.

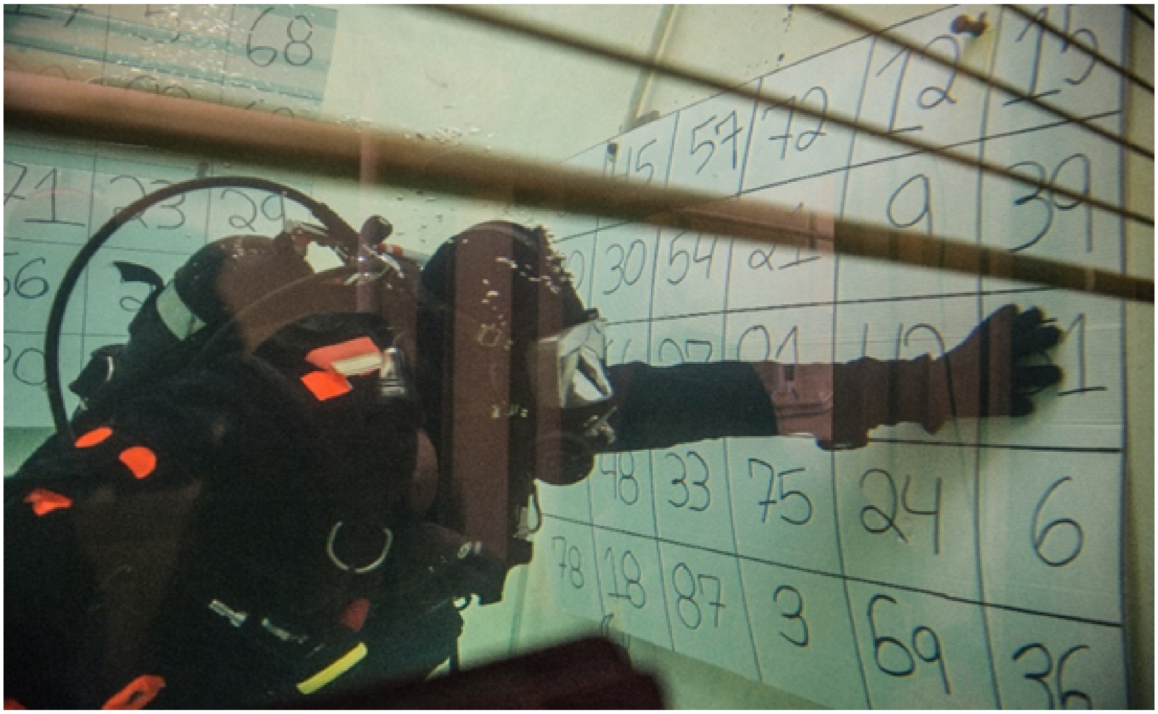

Figure 18: *Visual search task.*

2.4.6.6 Subjective questionnaires

At the end of each suit condition trial, a Task Load Index (TLX) questionnaire (Hart & Staveland, 1988) (Annex B, Figure B.1) as well as a custom Likert Scale questionnaire (Annex B, Table B.1) were distributed to obtain subjective measures. These subjective multidimensional assessments complemented the objective measures and provided additional insight into the effect of encumbrance on underwater task performance.

3 Results

3.1 Data analysis

A total of five participates, four males and one female, participated in this study. Due to limited number of participants, the statistical power of this study was deemed too low to warrant performing inferential statistical analysis. However, descriptive analysis was performed to identify performance trends.

Encumbrance is defined as the bulk, weight and stiffness of clothing and equipment. As the quantification of these factors require special considerations in the underwater environment (see Section 4.7) the analysis of 3D scans was not performed at this time . For the purposes of this analysis, encumbrance was defined as the restriction to divers' mobility The relationship between range of motion, the independent variable (IV), and task performance scores, the dependent variable (DV), were organized and presented with descriptive statistics such as mean and standard deviation. Cervical range of motion, whole body range of motion, and task performance scores were presented in histograms to summarize the data. Scatter plots with a line of best fit between each suit condition's DV and IV were utilized to analyze specific trends.

Subjective ratings of encumbrance and task load are reported without statistical inference, but trends and scores are discussed with reference to clothing condition and task performance.

3.2 Characterization of participants

Table 1 provides a summary of the demographic and anthropometric characteristics of the participants.

Table 1: *Participant demographic and anthropometric summary statistics (Mean ± SD). CC= Chest circumference, WC= Waist circumference C7= Height of the 7th cervical vertebrae.*

CAF Diving Experience (years)	**Age (years)**	**Weight (kg)**	**Stature (cm)**	**CC (cm)**	**WC (cm)**	**C7 (cm)**
6.8±5.6	35.0±7.2	82.6±10	175.0±8.8	103.0±9.2	88.4±7.6	149.4±7.8

Comparison of the weights of the dive suits revealed minor differences in dry weight, with the wetsuit being the lightest at 5.2±0.5 kg and the Fusion and Kodiak suits weighing 5.9±0.6 and 6.2±0.4 kg respectively. Addition of the CABA tanks added an average of 43.8 kg of supplementary weight to the participants (Figure 19).

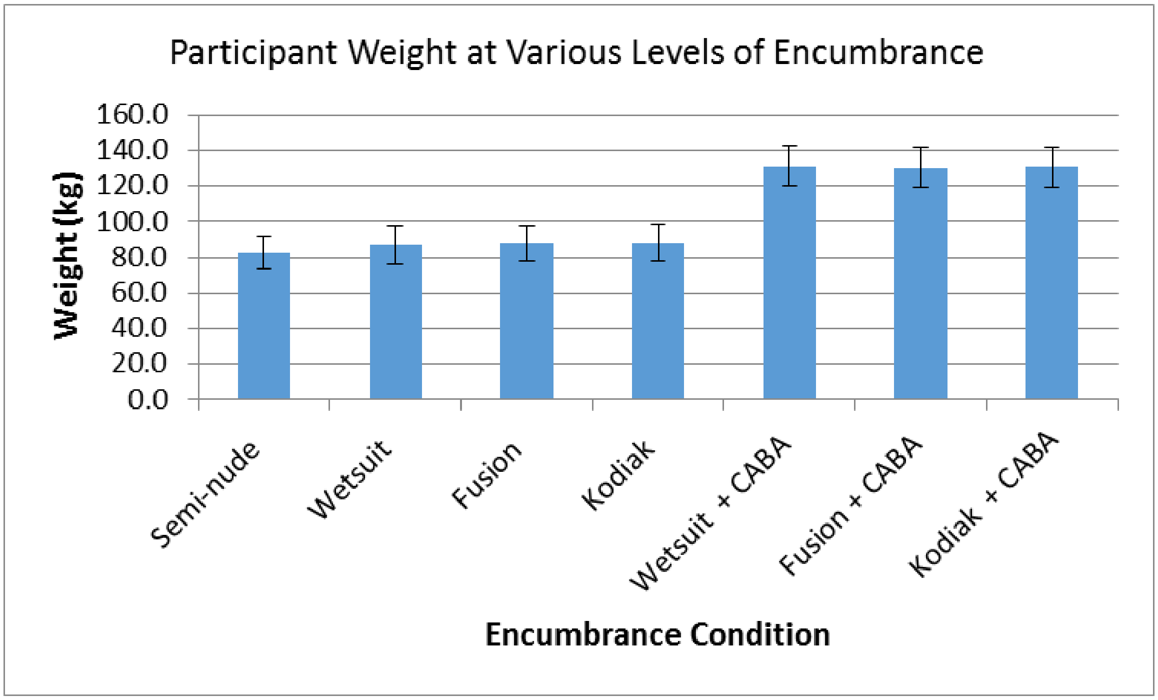

Figure 19: *Mean and Standard Deviation (SD) of weight of 5 participants under various levels of encumbrance.*

3.3 3D Scanning

To date, the three dimensional scans have not been analysed, as DRDC is currently working with academic and international partners to devise a standardized methodology to quantify bulk metrics from 3D scans of clothing and equipment. Figure 20 provides an example of these 3D scans in the various levels of encumbrance measured.

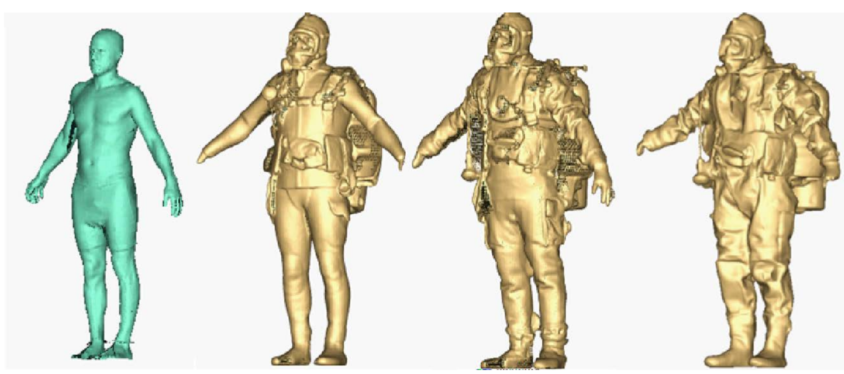

Figure 20: *Three dimensional scans of the: a) Semi-nude, b) Wetsuit, c) Fusion, and d) Kodiak dive suits with AGA mask and CABA tanks.*

3.4 Field of view

Figure 21, provides an overview of all participants' field in the AGA mask and baseline (no mask) condition. It is evident that, there is a large degree of inter-participant variability that appears to be greater in the left eye.

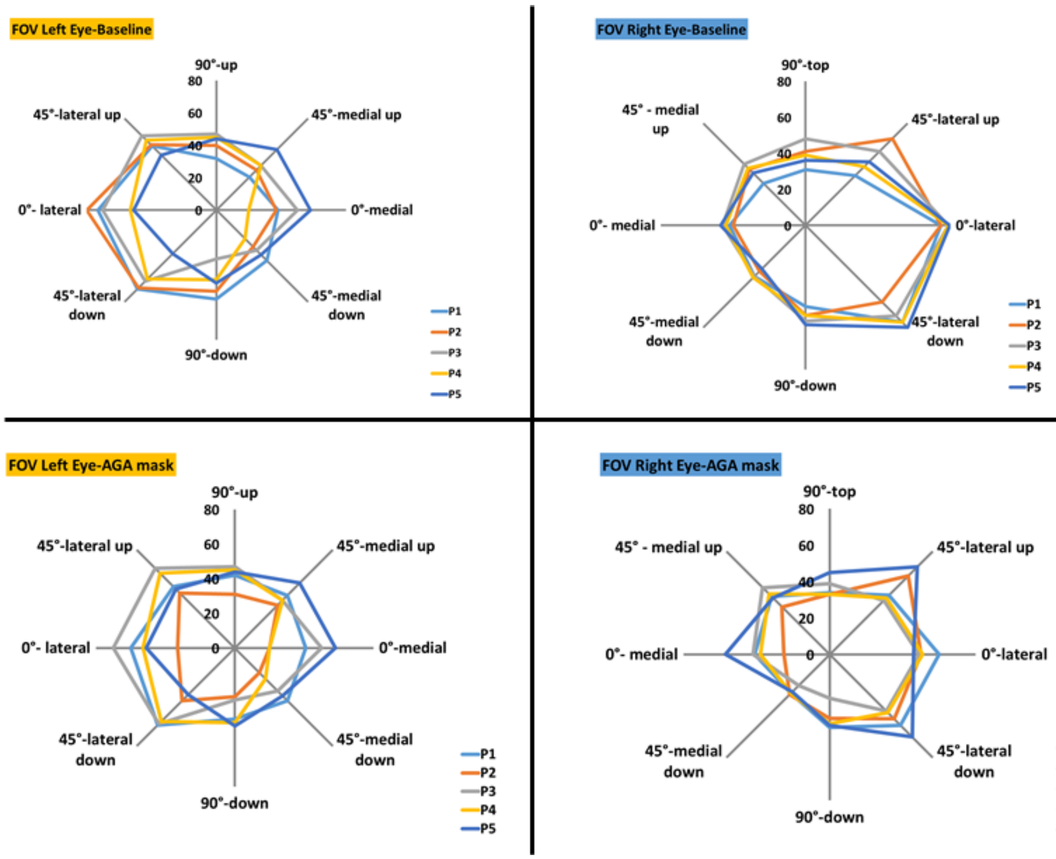

Figure 21: *Field of view map for each participants left and right eye, with and without (baseline) the AGA mask.*

By plotting the means of these values it is apparent that, when compared to the baseline condition, there is a bilateral restricted field of view with AGA mask affecting lateral and downward vision (Figure 22).

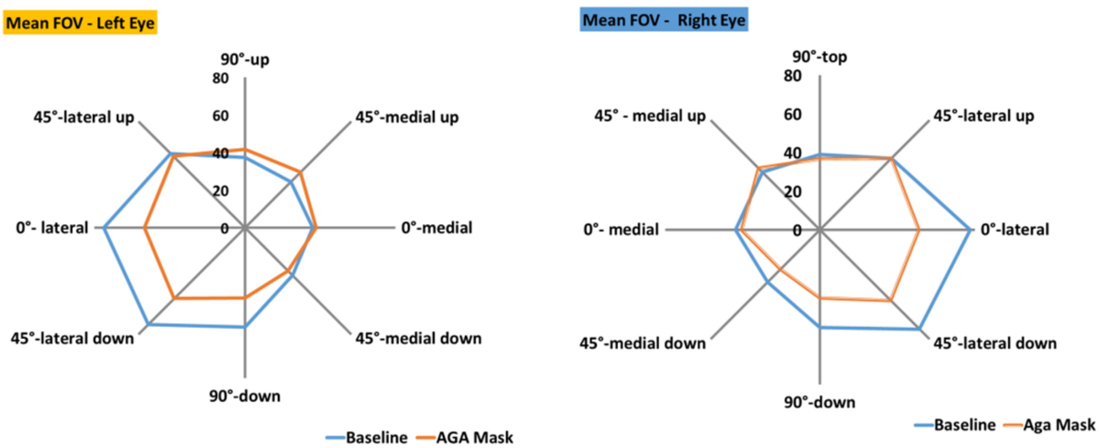

Figure 22: *Mean values for all participants field of view in the left and right eye, with and without the AGA mask.*

3.5 Range of motion

Figure 23 provides a comparison of cervical range of motion (CROM) across the four experimental conditions. Differences in CROM were observed between the levels of encumbrance with the semi-nude and Wetsuit condition appearing to allow the greatest CROM in all movements, with the exception of the Fusion, which performed slightly better than the Wetsuit in the lateral left flexion task. In general, the Fusion and Kodiak suits performed similarly across all range of motion movements, with the Fusion displaying better performance in right rotation, flexion and lateral left flexion and the Kodiak allowing greater neck extension. Right rotation showed the greatest difference between each of the suit conditions with a consistent decrease in CROM.

When compared against the seminude condition, all encumbered conditions provided some degree of restriction to range of motion, with the Fusion and Kodiak tending to restrict motion more than the wetsuit in all CROM motions with the exception of lateral left flexion Figure 24. Right cervical rotation is restricted the most of all motion, likely due to the collision between the mask regulator and beacon mounted on the diver's right shoulder strap.

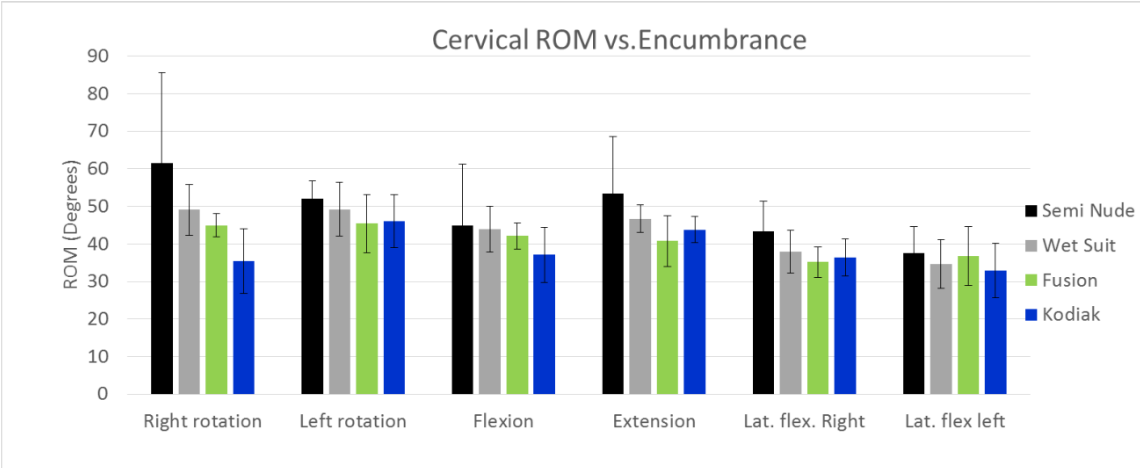

Figure 23: *Comparison of mean cervical range of motion movements in various levels of encumbrance.*

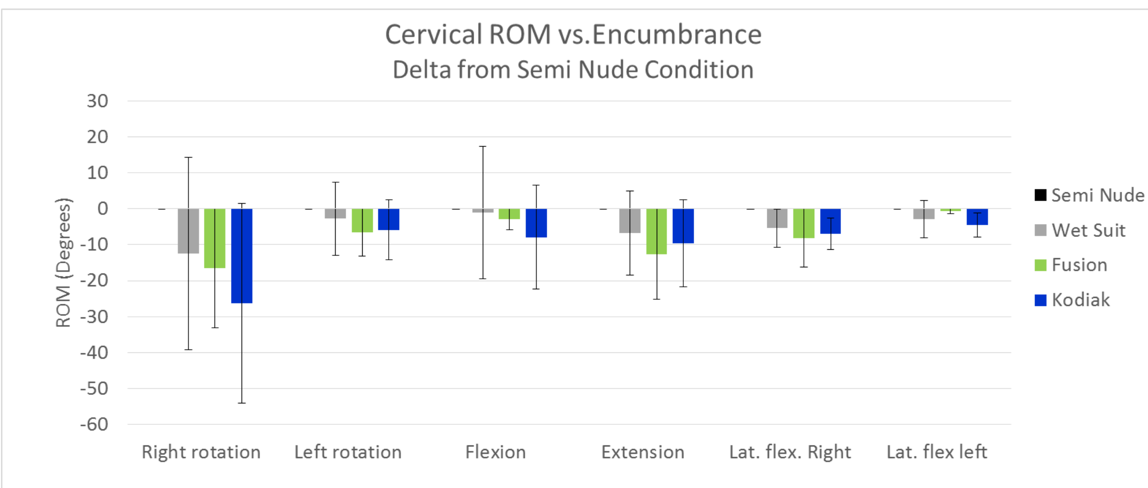

Figure 24: *Comparison of mean cervical range of motion as compared to semi-nude reference.*

Figure 25 provides a comparison of whole-body ROM across the three suit conditions. Recall that due to the cool (20°C) water temperature, in-water tasks were not completed in the semi-nude condition. For all in-water tasks, the wetsuit was considered to be the reference condition. Differences between suit conditions were subtle across all movements with the possible exception of shoulder flexion and abduction where it appears that the wetsuit afforded slightly more shoulder mobility. Due to the low number of participants in this study, these results indicate trends across suit conditions and should not be assumed to be conclusive.

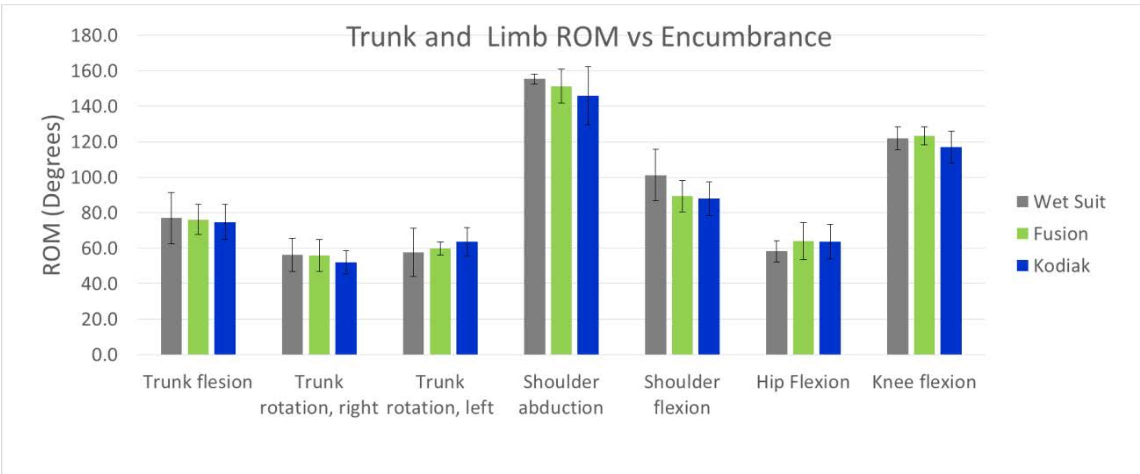

Figure 25: *Comparison of trunk and limb mean range of motion, in various levels of encumbrance.*

3.6 Task performances

Figure 26 indicates that performance in the Wetsuit condition was poorest in the fine motor dexterity tasks (i.e., Nuts and Bolts, Rope Tying). In contrast, the Fusion suit condition was associated with the poorest performance in the gross motor, (i.e., mobility related Weight Transfer and Visual Search tasks). Comparing the Fusion and Kodiak suits, fine motor performance was similar between the two suits however, the Kodiak was associated with markedly better performance in the weight transfer and visual search tasks.

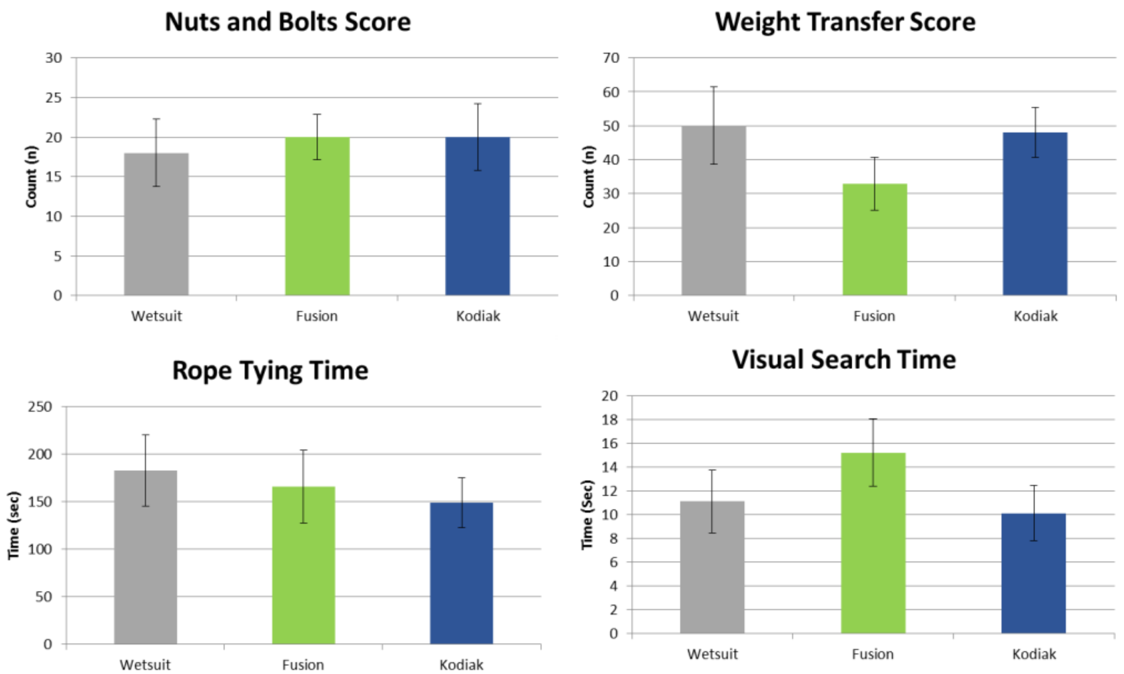

Figure 26: *Task performance scores for A) Nuts and Bolts, B) Weight Transfer, C) Rope Tying, and D) Visual Search in the Wetsuit, Fusion, and Kodiak suit conditions.*

3.7 Range of motion vs. Task performances

Figure 27 provides exemplars of the relationship between CROM and Visual Search Task performance in the three suit conditions. In each example, the Fusion was associated with the slowest completion of the visual search task, whilst having the most restriction to CROM in extension, left rotation, and right lateral flexion motions. Despite allowing the greatest CROM, the performance in the wetsuit was slightly poorer than in the Kodiak suit.

Figure 27: *Mean cervical range of motion in a) extension, b) left rotation, and c) right lateral flexion, against visual search task times in the Wetsuit, Fusion, and Kodiak suit condition.*

A reverse trend was noted in the Nuts and Bolts task (Figure 28) where the suit most restrictive to horizontal shoulder ROM and CROM flexion (Kodiak) was associated with best performance in the Nuts and Bolts task. While this may seem counterintuitive, it suggests that certain tasks may benefit from restricted range of motion by providing a stabilizing function during fine motor tasks.

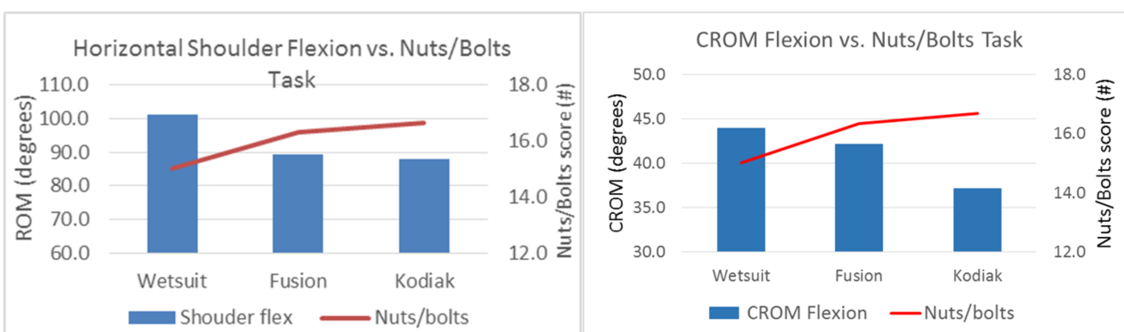

Figure 28: *Mean a) horizontal shoulder flexion and b) cervical flexion against the Nuts/Bolts scores in the Wetsuit, Fusion, and Kodiak.*

Increased range of motion of the upper body, was associated with a trend towards improved performance in the Rope Typing Task (Figure 29). Observation of these data suggest a curvilinear relationship such that improvement in task is not apparent until shoulder range of motion exceeds an approximate 90 degrees, however, due to the low number of participants, the significance or validity of this observation cannot be determined.

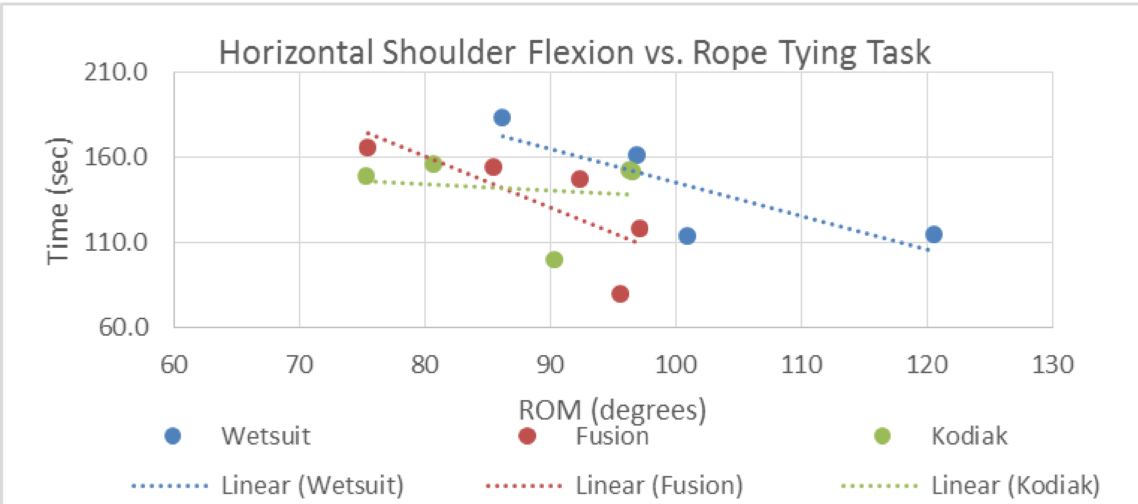

Figure 29: *Participants' rope tying times plotted against range of motion (ROM) for horizontal shoulder flexion in all conditions.*

3.8 Subjective feedback

Figure 30 provides a summary of responses to the custom, 5-point Likert diving questionnaire. In general, the majority of responses tended to reside in the 'undecided' column indicating that the participants felt neither adversely encumbered or aided by the suit worn. Participants wearing the Wetsuit and Kodiak tended to indicate that they did not feel that the level of restriction and bulk adversely affected functional task performance. Question 10 elicited the greatest discrepancy between the suit conditions with participants indicating that they agreed that the bulk and restrictiveness of the Kodiak and Wetsuit did not affect their task performance. In comparison, the participants wearing the Fusion suit tended to feel that their performance was adversely affected by this suit, as indicated by disagreeing with this statement.

Figure 31 Provides the responses to the NASA Task Load Index (TLX), indicating that, on average, participants found the performance tasks to be low to moderately demanding. In all but the one question, task performance in the Fusion was ranked as the most demanding of the three suit conditions. Wetsuit and Kodiak conditions scored similarly with the exception of task Performance and task Frustration which was scored as being less demanding in the Kodiak suit.

Question	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
1. The suit felt overly restrictive/bulky and diminished my ability to move through simple ranges of motion		W K	F		
2. The suit design was restrictive/bulky and prevented me from performing fine motor tasks (e.g. nuts and bolts, rope tying) optimally		W	F K		
3.I had difficulty performing the "gross motor-transfer" task due to the suits restrictive fit		W K	F		
4.I had difficulty performing the "gross motor-transfer" task due to the suits configuration of bulk		W K	F		
5. As a means to compensate for a restricted field of view while wearing the AGA mask, large head or body movements were needed in this suit			W K F		
6. My "In water- field of view" performance could have improved if the restrictiveness of the suit were to be minimized			W K F		
7. My comfort was affected in this suit due to its restrictiveness and the configuration of bulk		K	W F		
8. Working carefully with small objects in front of me was difficult and thus my fine motor performance was jeopardized due to the suits restrictiveness		W K	F		
9. Maintaining a static position while working carefully with small objects was difficult.			W K F		
10.The level of bulk and restrictiveness in this suit did not affect my functional task performance		F		W K	

Figure 30: *W= Wetsuit, K= Kodiak, F= Fusion. Custom Likert scaled diving questionnaire with the order of mean responses upon wearing the Wetsuit, Kodiak, and Fusion.*

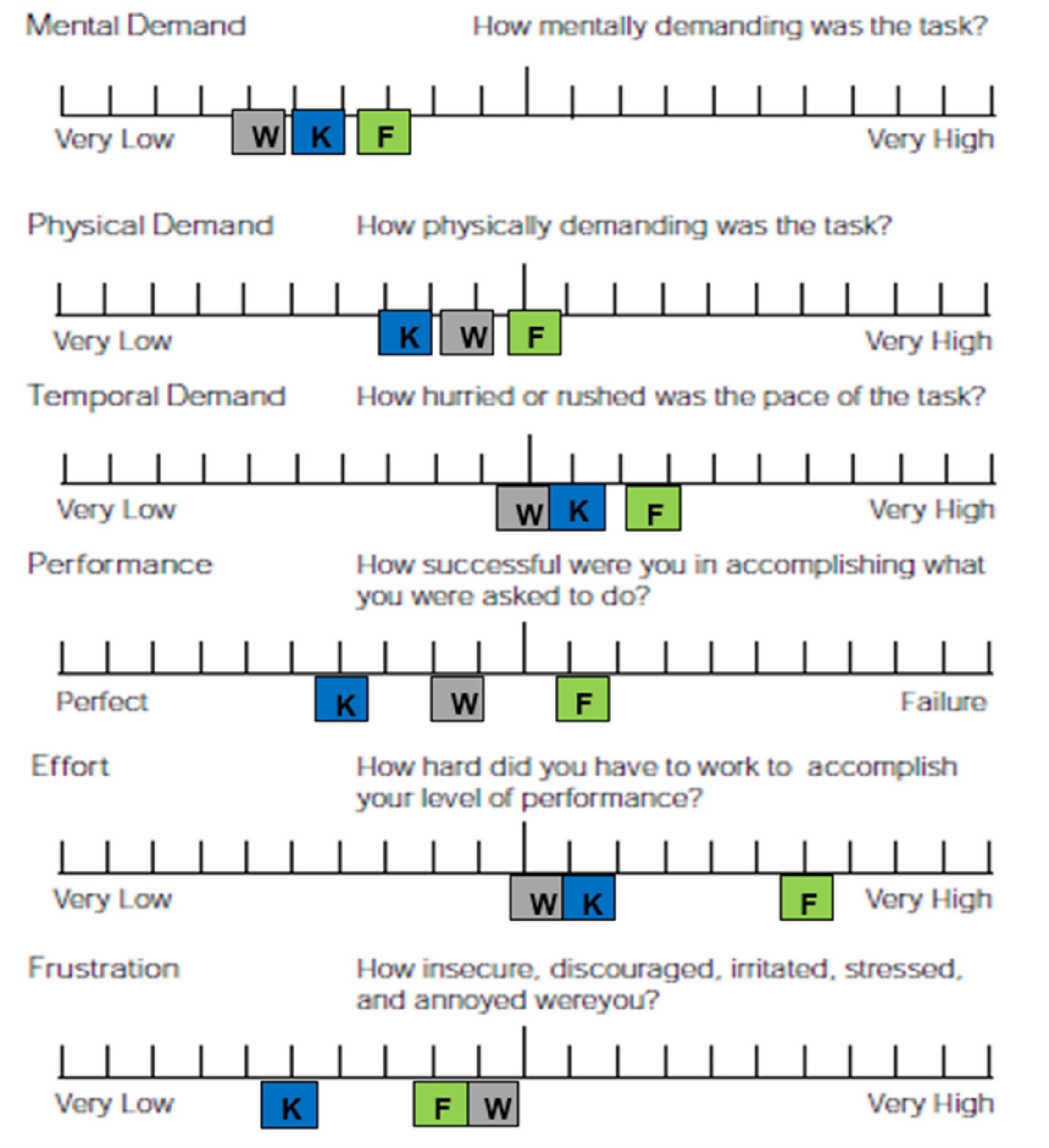

Figure 31: *W= Wetsuit, K= Kodiak, F= Fusion. Task Load Index questionnaire with the order of mean responses upon wearing the Wetsuit, Kodiak, and Fusion.*

4 Discussion

Due to the small number of participants in this pilot study (5), inferential statistics were not possible. As a result, the data presented in this report are not necessarily generalizable to a broader, diver population. Despite the limited scope and statistical power of this study, it was apparent that there were trends in task performance and subjective ratings associated with wearing different dive ensembles. This is important as it suggests that task performance may be explained by differences in the configuration, fit and restriction of movement afforded by different diving ensembles. The following discussion focuses on the relationship between dive ensemble encumbrance and task performance. This is followed by an assessment of key challenges and opportunities to inform the development of ergonomics-based methodologies to conduct human factors research to conduct performance based assessment of diver ensembles and equipment.

4.1 CROM vs. Visual search

A comparison of cervical range of motion against the participants' visual search times revealed a noticeable trend indicating that participants wearing the Fusion suit demonstrated the least amount of CROM in three of the six movements evaluated (extension, left rotation, and right lateral) and was associated with the poorest task performance. This trend supports the stated hypothesis and coincides with Alfano & Michel (1990), Toet (2007), and Toet's (2008) conclusions regarding large head movements needed to compensate a restricted field of view. Additionally, this trend supports findings from Son et. al (2010), whom concluded that an increase in encumbrance would be associated with a decreased task performance.

In lieu of a semi-nude immersed condition, the wetsuit was intended to act as the in-water baseline condition due its reduced bulk, yet visual search performance was not superior to the Kodiak condition despite consistently demonstrating greater CROM. This is in contract to a study on spinal manipulation therapy found that an improvement of next rotation by only 4 degrees significantly improved Fitt's Task performance (Passmore et.al., 2010). Assessment of the subjective feedback questionnaires indicate that the wetsuit was scored as requiring the least amount of mental and temporal demand, and effort. Meanwhile, it was also scored as having the highest level of frustration. As the participants indicated that they were not as familiar with the wetsuit as the Kodiak and Fusions suits, a greater emphasis on conducting familiarization trials prior to the beginning of data collection should be put into effect in future studies to account for learning effects. Additionally, it is possible that underwater Visual Search performance is based on multifactorial considerations as the diver must counter buoyancy and viscous moments and forces to manipulate the body in 3D space. Thus differences in CROM may have been countered by other factors inherent to the suit condition.

4.2 Fine motor tasks vs whole body ROM

Overall, a greater horizontal shoulder flexion was associated with quicker rope tying times. Similarly, an increase in right sided trunk rotation resulted in an increase in the number of weights transferred. This relationship of mobility and performance agrees with Coca et. al (2010) and their findings, whom concluded that a decrease in mobility can negatively affect performance. Interestingly, the relationship between rope tying performance and ROM suggests a curvilinear trend such that performance appears to show increased rates of improvement above 90 degrees of shoulder flexion ROM. This type of relationship can be useful for establishing minimum mobility requirements of dive suits.

The inverse relationship seen with the horizontal shoulder flexion versus the Nuts and Bolts task highlights an important distinction between gross motor and fine motor tasks. While it was hypothesized that encumbrance will decrease ROM and task performance, in this case, a greater ROM was associated with poorer fine motor task performance. Through observations, Nuts and Bolts task involved little movement of the upper limbs and the divers remained in a relatively static position throughout the task. Meanwhile, the Rope Tying task involved greater movement of the upper limbs to manipulate the rope and unravel the knots. This dissimilarity between fine and gross motor tasks may account for the contrasting results. There appears to be a competing requirement for stability and flexibility which may operational considerations in specifying gear for specific missions. Greater ROM may facilitate tasks that involve greater movement at a joint; meanwhile increased suit stiffness may stabilize the upper body/shoulder joint, aiding the performance of a dexterity task that requires stability and precision. Furthermore, the Nuts and Bolts task was performed at a fixed station, meanwhile the Rope Tying task was, performed in an unconstrained space, requiring larger body movements to maintain stability. In their review of manual dexterity in open ocean underwater tasks, Hancock & Milner (1986) attributed the stability of the work surface as an important contributor to increased task performance. Extending this conclusion to the current study, it is plausible that regional and restricted ROM may be a more suitable predictor of fine motor task performance when body stability is required (e.g. when working at a fixed work station).

4.3 Range of motion

A dynamic warm up was performed before each dryland and in-water ROM activity to increase flexibility and to decrease the risk of injury. Roberts & Wilson (1999) showed that holding a static stretch for 15 seconds resulted in greater ROM, as opposed to holding it for 5 seconds. This reveals the magnitude in which stretching can alter mobility. All participants were instructed on appropriate static and dynamic stretches and warm up activities, however, the discipline to which they were performed was uneven. An insufficient or inappropriate warm up could adversely affected measures which can greatly affect interpretation of the trend. Validity and reliability of range of motion and repeatability of joint angle differences may also be low due to a lack of participant motivation, difficulty following the standardized technique, and difficulty in identifying landmarks. Physiological factors such as muscle strength and endurance should be implemented in future studies comparing ROM against task performance, since some participants may be able to achieve the same distance with more or less effort.

4.4 Suit differences

Overall, there was little, consistent discernibility between diving ensembles and task performance. This is not particularly surprising given the low number of participants and variability of individual performance for each task. Understanding this variability is crucial to determining the minimal number of participants required to provide sufficient statistical power for detecting differences in performance (Guo et al., 2013).

A second factor which must be considered is the possibility that the tasks were not sufficiently challenging to the participants. This is exemplified by the subjective ratings of the NASA Task Load Index questionnaire, that revealed that participants reported these tasks to be low to moderately demanding. It is believed that by increasing the level of difficulty and challenging the working ranges and limits, discrimination between suit conditions would increase. As the EDUG static tank is quite small, mobility tasks such as the visual search or weight transfer tasks may not have been as challenging as if there were conducted in a larger body of water.

Finally, as a complete set of sizes of each dive suit were not available, participants were affected by the sizing and fitting of the suits. Moreover, participants indicated that they were not as familiar with the wet suit as the Kodiak or Fusion. These suits are often custom-made or issued based on the individual's anthropometric measures. As a result, borrowing of suits between participants was a common occurrence. Even though the participants may have successfully donned the suit, it does not necessarily reflect the manner in which the suit is intended to fit in local areas. Suits that are too large or too small could affect the validity of these measures. Future studies should include divers bring their own fitted or custom suit. Conversely, when evaluating non-issued garments, an operational definition of fit so that dive suits can be issued according to a standardized methodology across participants. Once an optimal fit has been achieved, a familiarization trial should be held to ensure that the diver reaches a baseline level of task performance and familiarity with each suit.

4.5 Operations and task analysis

Underwater tasks performed in this study were based on an assessment of MCM tasks elicited through interview with EDUG subject matter experts, review of RCN dive operations manuals and external literature. In addition to limitations of time and scope, tasks were also selected based on suitability for implementation within the EDUG static dive tank.

The Human Factors Test Plan (HFTP) for the Canadian Armed Forces diving program (Tack and Angel, 2015) clearly outlines the requirement for the development of operational scenarios and the performance of function and task analysis to inform the operational conditions and performance requirements of the diver and equipment to achieve mission success. This process can then be used to define the personnel, logistics, environmental conditions, dive mission scenarios/vignettes, tasks and performance metrics that would contribute to the development of experimental test protocols.

The HFTP provides a number of valuable references to assist with the identification of operationally specific scenarios and associated divers tasks. Relevant scenarios can also be identified through the support of the Clearance Diver Assessment Centre (CDAC). Additionally, there has been a wealth of studies detailing mine counter measure task analysis and performance standards commissioned by DRD/CFEME. In particular, a literature search of DRDC/CFEME literature has identified 20 publications by Morrison and colleagues of Shearwater Human Engineering (Annex C) on optimizing the performance and safety of mine counter-measures diving. Unfortunately, these resources were not available to the authors at the time of this study, however, a detailed review of these reports and the associated recommendations should be valuable in the planning of future mine counter-measures research as they provide valuable information on MCM task analysis, ergonomic recommendations and guidelines and proposed methods for evaluating MCM procedures using new technologies.

4.6 Environment

The EDUG static dive facility was a valuable asset for conducting a pilot evaluation of the ergonomic assessment methods and technologies employed in this study. In order to perform more comprehensive evaluations of complex operations requiring environmental factors (e.g. light, thermal, turbidity, current, or waves), mobility (e.g. transit, jackstay searches or Pouncer operations) or team-based activities (e.g. zodiac based dive operations), it is essential that suitable facilities with qualified staff and environmental controls be sourced.

Facility concepts, providing unique capabilities, for diving research are the Flume Tank at the Fisheries and Marine Institute of Memorial University of Newfoundland (Figure 32), Helicopter Underwater Escape Training (HUET) facilities located at institutions such as: Memorial University, and Survival Systems Training and Survival Systems Limited in Dartmouth, Nova Scotia. Human Sciences research personnel with extensive experience in maritime human factors research are available locally at Memorial (St. John's) and Dalhousie (Halifax) Universities.

Memorial University's Flume Tank is the world's largest at 8 metres wide x 4 metres deep x 22.25 metres long and a water depth of 3–4 meters and can generate currents of up to 2 knots full scale. Dyes can be added to the water to manipulate the turbidity of the water. A large viewing gallery provided experimenters with the ability to observe experimental trial in progress. Being a research facility, the flume facility is well instrumented for data acquisition, underwater video and motion analysis.

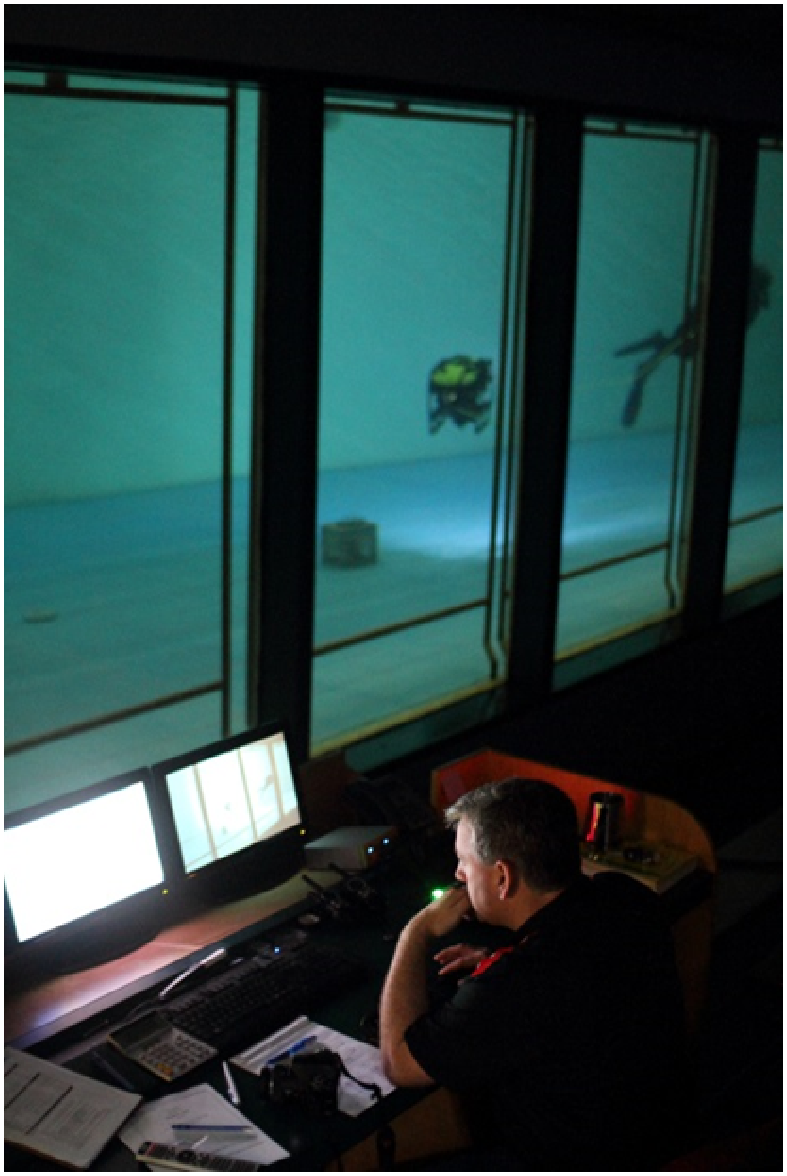

Figure 32: *Memorial University's flume facility demonstrating use in diving operations research. Copyright by the Fisheries and Marine Institute of Memorial University of Newfoundland. Reprinted with permission from Paul Winger, 12 September 2017.*

Environmental theaters and HUET trainers provide a unique opportunity to evaluate surface and subsurface operational scenarios. Memorial University, Survival Systems Limited and Survival Systems Training offer facilities that can control multiple environmental conditions such as wind, wave height, fog, turbidity and lighting conditions. As an example, the Marine Aviation Survival Training facility (MAST) at Survival Systems Training is a

25m length x 14m width x 5m depth that employs a unique wave generator that can produce 7 different wave patterns (including confused seas) and up to 1.8m in wave height.

As environmental theatres and HUET trainers are used for training purposes, they are well supported for ergonomics research by including large aprons for staging test equipment and change room facilities. Simulated ships decks are provided to allow for jump platforms and marine emergency egress and ingress systems (e.g. slides, ladders, scramble net). The MAST system includes a helicopter rescue hoist attached to a 7m static or dynamic mount to simulate helicopter extraction.

4.7 Quantification of system encumbrance and mobility

4.7.1 Bulk

Performance metrics such as time to task completion and subjective ratings appear to be an effective method to determine the net operational effectiveness of a diving system, however, it does not reveal the structural differences between difference equipment configurations which may give rise to these results. Typically, the encumbrance of clothing and equipment is defined along three vectors – bulk, stiffness and weight.

Bulk may be determined by obtaining physical measures of the diver wearing dive ensembles using traditional methods such as measuring tape or calipers or 3D laser scanning techniques to capture the dimension and shape data. Traditional methods have the advantage in that, accurate measurements of discrete locations can be obtained easily in both the laboratory or field setting. Second, for looser fitting ensemble such as dry suits, the blousing of the material can be compressed to provide a more accurate assessment of the effective bulk (Kozey et al., 2005) that may be experienced while under hydrostatic pressure while diving.

3D scanning, provides detailed information regarding shape and bulk distribution of the equipment in relation to the diver's body. A limitation of 3D scanning is that it does not permit the compression of clothing and equipment, hence the shape and volumetric data obtain may not be suitable for dive applications. Algorithms such as those developed for ClothCap (Pons-Moll et al., 2017) provide a capability to model the draping of clothing of 3D body scans and predict its conformation to the body during motion. It would be interesting to investigate the feasibility of applying these algorithms or methods to a diving scenario.

It is possible that some of these challenges can be mitigated by scanning divers wearing only the hard, non-compressible equipment (e.g. mask, tanks, regulator) during scanning, but this would neglect the parameterization of the clothing and equipment ensemble as a whole. DRDC has conducted preliminary research to develop methods to quantify clothing and equipment bulk on dismounted soldiers (Jones et al., 2015), however its application to the evaluation of bulk during dive operations has not been validated. The 3D scan data collected as part of this study can be used to adapt these methods to account for compression due to hydrostatic pressure and better inform the quantification of dive ensemble bulk. This could be accomplished by investigating additional 3D image capture techniques, such as photogrammetry, to obtain objective data on how dive clothing shifts and conforms to the body during water immersion. This could theoretically be modeled in a virtual environment using shape analysis or finite element modeling techniques to provide an objective prediction of immersed bulk and restriction to motion.

4.7.2 Ensemble Stiffness

Ensemble stiffness is a function of the material properties of the clothing and equipment, size and distribution of the equipment and its attachments and fit. The evaluation of ensemble stiffness is typically determined by a functional range of motion test as described in Section 2.4.4. Cervical range of motion measures were conducted on dry land as it was not dependent on balance or posture and it was assumed, rightly or wrongly, that there would be little interaction between the medium (air or water) that the diver was placed in and task performance. Initial attempts at measuring CROM in-water proved unreliable, as it was difficult to fix the torso to isolate head motion. Admittedly, it would have been preferred to conduct all range of motion measures immersed. If this study were to be repeated, greater care would be exercised in developing a technical and methodological solution to facilitate immersed CROM measures. Range of motion of the torso, legs and arms is likely affected by the fit or stiffness of the compressed diving clothing as well as the mass distribution of the equipment worn by the diver. For this reason, it was decided to perform the range of motion exercises in the static tank to account for hydrostatic pressure, buoyancy and the hydrodynamics of the water. While likely a more valid measure of ensemble stiffness, challenges in maintaining posture and balance while performing the range of motion activities were noted. This can be resolved by providing a foot hold weighted or secured to the floor of the tank to provide stability while performing range of motion tasks. On the other hand, if one is interested in the functional effect of ensemble stiffness on balance and range of motion tasks, then an unrestrained posture is desirable.

4.7.3 Ensemble weight

Physical burden is typically identified as the mass and mass distribution of the physical load carried by the warfighter. The effect of the load carried by diver affects performance very differently as weight helps to counter the buoyancy of the diver and equipment, but can also adversely affect mobility and stability if the load is excessive or unbalanced. In certain circumstances, strategically placed weight may increase stability when working on a platform or ocean floor. Thus, gross dry weight of the diver may not necessarily be predictive of underwater performance or encumbrance. It is recommended that a method to determine immersed weight, buoyancy and moment of inertial/buoyancy be developed to develop acceptable standards and specifications for diving ensembles and equipment to optimize diver performance.

4.7.4 Motion capture

Range of motion was quantified using 2D video analysis of high contrast markers placed on the diver. This method is typically sufficient for simple movements that occur in one plane such as those evaluated in this study. For more complex movements, such as those executed in underwater tasks, 3D motion analysis is required. This can be accomplished used two video cameras and a software tool such as ProAnalyst 3D (Xcitex, Woburn, MA). A second option is to use an optical tracking system built for underwater application. Qualisys (Qualisys North America, Highland Park, IL) has successfully developed an underwater optical motion capture system that has been used for kinematic analysis of swimming (Olstad et al., 2012) (Figure 33). Currently, CETTs provides a ProAnalyst 3D software capability as well as Qualisys Track Manager motion capture software. The Qualisys cameras available through CETTs are not suitable for underwater application, however, the Fisheries and Marine Institute of Memorial University of Newfoundland possesses suitable cameras to facilitate human factors studies in their Flume or HUET and Environmental Theatre. Data captured at Memorial University would be compatible with CETTs Qualisys software for analysis.

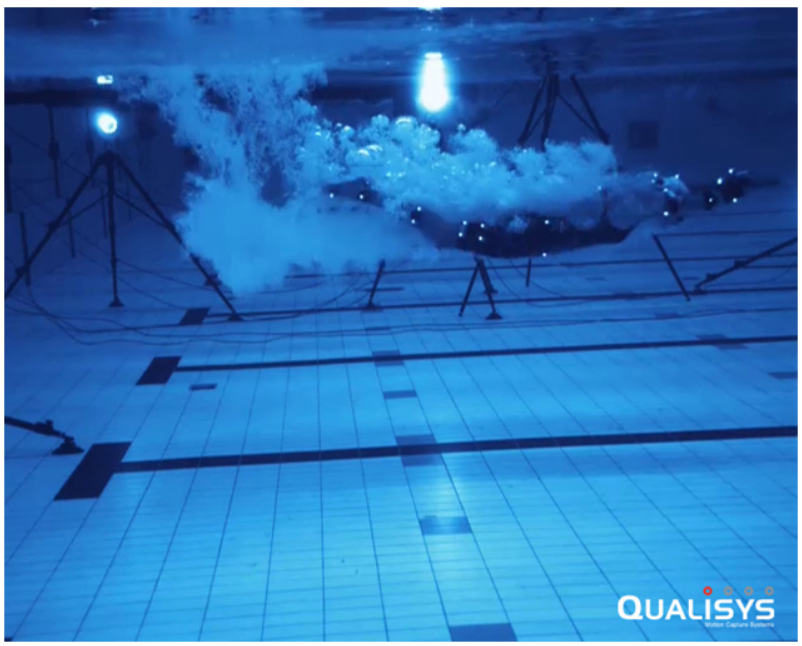

Figure 33: *Example of the Qualisys system adapted for underwater motion capture. Retrieved from `https://www.flickr.com/photos/qualisys/`. Reprinted with permission from Scott Coleman, Qualysis, NA, 11 September, 2017.*

A major drawback with video and optical tracking systems to capture the motion of encumbered individuals is that the tracking markers must be placed on the surface of clothing and equipment. As a result, the underlying motion of the diver may not be accurately tracked.

This is particularly true when clothing and equipment is not tightly coupled to the diver's body. A third technology that may provide accurate body motion tracking are inertial motion units (IMU's) and have been validated in swimming application (De Magalhaes et al., 2014). IMU's rely on inertial sensors and accelerometers to track relative motion and have been used successfully in biomechanical applications. As IMU's are subject to magnetic interference, they can be problematic for use in ferrous environments such as vehicles or buildings. Fortunately, dive equipment used for mine counter measures operations are devoid of ferrous or magnetic materials, making the use of IMU's a very attractive option. CETTs currently possesses a Synertial inertial motion capture system (Synertial U.S., Emeryville, CA), that could be adapted for diving applications by waterproofing the sensors and the addition of a data logging unit to replace the Bluetooth^{TM} and WiFi communication systems that are typically employed.

4.7.5 Biomechanical modeling

While motion capture systems provide kinematic (motion) data, it is often important to understand the physical forces required by the diver to meet the challenges imposed by the dive equipment, task and underwater environment. Modeling of these forces is typically achieved through biomechanical analysis using digital human modeling tools such as JACK (Siemens, Plano, TX), RAMSIS (Human Solutions of North America, Inc., Cary, NC) or Visual 3D (C-Motion, Germantown, MD), all of which are available through CETTs. A limitation of these tools is the fact that that they do not account for the unique forces and moments (e.g. hydrostatic pressure, buoyancy, and currents) experienced by divers. While few researchers have attempted to develop suitable models to assess underwater biomechanics (Seireg et. al, 1971), these models are not generally robust or available in commercial tools. Of interest, however is the SWUM (Swimming human Model) developed by a team led by Prof. Motomu Nakashima (2016).

SWUMsuit is a freely available software application that permits the analysis of four swimming strokes, accounting for fluid forces and body inertial. The output of this software can be uploaded to AnyBody Modeling System^{TM} (AnyBody Technology, Salem, MA) for biomechanical analysis. An example of the output of the SWUMSuit model as represented in AnyBody Modeling System^{TM} is provided in Figure 34.

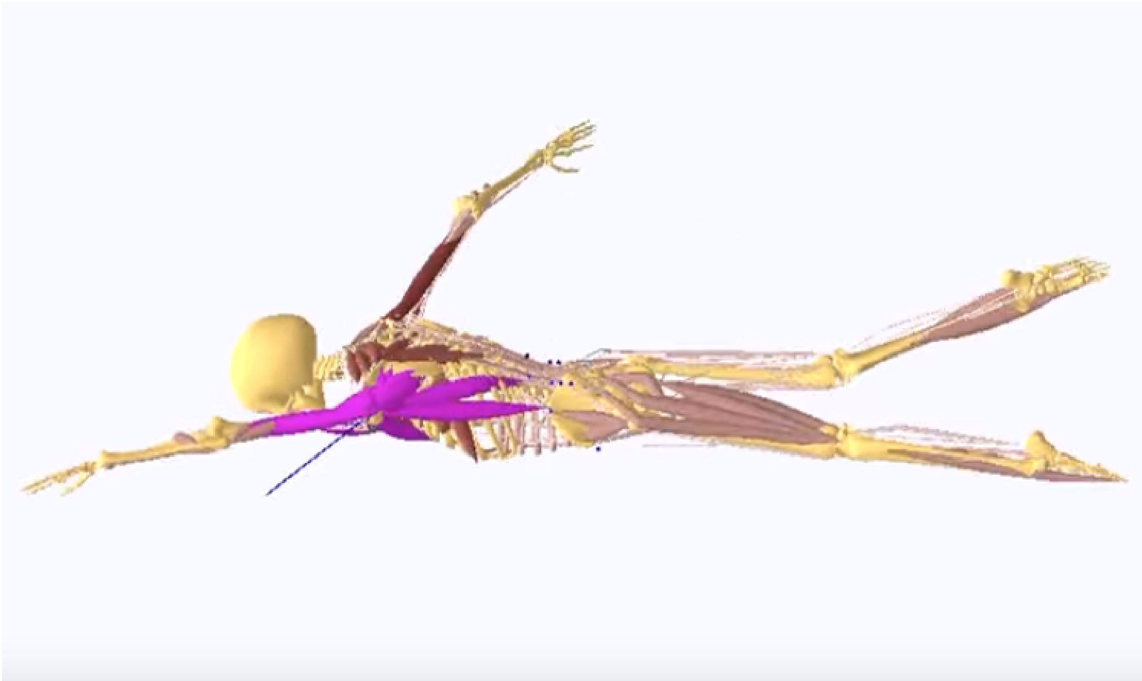

Figure 34: *Biomechanical analysis of the front crawl as represented by the SWUMsuit model using Anybody Modeling System^{TM}. Retrieved from* `http://www.swum.org/anybody_crawl.avi`*. Adapted with permission from the author, Motomu Nakashima, 15 September 2017.*

Currently, SWUMsuit software does not account for the inclusion of dive equipment and encumbrance, however, it represents a potentially useful building block towards developing a virtual modeling tool for dive applications.

5 Conclusion

A pilot study, investigating the effect of encumbrance on diver underwater task performance, was conducted to evaluate the application of tools and methods developed in the Comprehensive Ergonomics-based Tools and Techniques (CETTs) project to a diving scenario. Novel CETTs-based tools that were employed include 3D whole body scanning and optical and video based motion capture. The central objective of this pilot study was to provide preliminary information for the development of a standardized methodology to support the human factors evaluation dive clothing, equipment and platform.

Despite the low number of participants (5), trends were noted in task performance between the different dive suit (encumbrance) conditions across. In certain cases encumbrance, as defined as an decreased range of motion, were associated with poorer mobility, gross motor task performance, and visual search efficiency. Performance on a fine motor task appeared to benefit by the most restrictive encumbrance condition, possibly due to providing greater postural stability in the underwater environment. Despite the challenges of quantifying encumbrance and its effect on dive task performance, it was demonstrated that ergonomic measuring techniques can be adapted to the immersed environment. There are, however, several technical and procedural considerations that must be followed to ensure optimal quality of data:

- First, when conducting range of motion measurements, maintenance of proper posture and stability of the participant is paramount to ensure valid and repeatable measures. Buoyancy, fluid resistance and currents can interfere with the ability to perform the range of motion activities correctly. While ankle weights were provided to the participants in this study to improve stability, it is likely that a more robust solution be devised.
- Second, range of motion was measured using video analysis to track markers placed on the diver's suit. As it is possible that the suit motion is not perfectly coupled to diver motion, errors in movement tracking may be introduced. The use of an inertial-based motion tracking system applied to the diver's body would mitigate this concern.
- Finally, encumbrance may be described in terms of the bulk, weight and stiffness of clothing and equipment. Hydrostatic pressure, buoyancy and hydrodynamic forces interact with a divers' suit and equipment in such a way that the traditional, land-based paradigm of measuring encumbrance cannot be easily applied. Future research should focus on identifying and parameterizing key aspect of diver encumbrance that are influence by the immersed environment.

The EDUG static tank provided a suitable environment for evaluating piloting this test methodology, and may be adequate for evaluation of static tasks. To extend this capability, flume and environmental theatre facilities within Canada have been identified which provide a state-of -the-art technical capabilities, ability to control environmental variables (e.g., sea state, turbidity and current), large water volume and safe operating conditions. Finally, as technical evaluation of diver performance can be costly and technically challenging, a OpenSource biomechanical modeling approach has been identified, having the potential to be adapted to a diving scenario. This would allow the researcher to conduct computer-based "what if" simulations to better understand the interaction between the diver and their clothing and equipment and guide future research.

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Annex A Participant information sheet

The following is an information sheet provided to individual considering participating in this study.

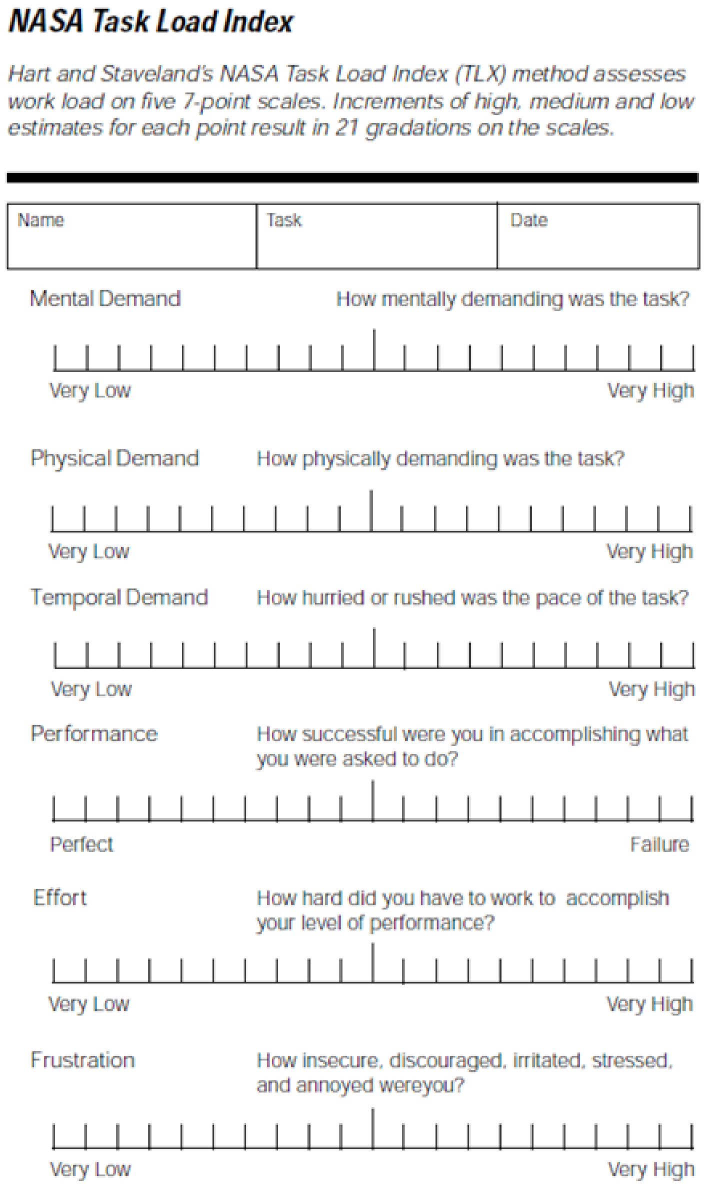
Purpose	The purpose of this pilot study is to assess and understand all of the dimensions within diving which are operationally relevant, as well as their relationship to encumbrance and task performance. The ultimate goal is to develop a methodology that can be implemented in future studies, and to provide future recommendations through acquisition.
Procedure	Participants will undergo a series of dry land and under water tasks. Dry land tasks include 3D whole-body laser scanning in a semi-nude (shorts and sports bra for women) and each of three diving suit conditions while wearing an AGA dive mask and Compressed Air Breathing Apparatus (CABA) tanks. Visual field of view and neck range of motion will also be measured. They will then enter an 8' x 8' x 10' dive tank and execute underwater whole-body range of motion, fine motor, gross motor, and field of view tasks. The range of motion task will be video captured for subsequent motion analysis. This sequence of tasks will be repeated for each of the 3 suit conditions, although the suit order will be randomly assigned.
Voluntary Participation	Your participation is completely voluntary. You may end your participation at any time, and you may refuse to conduct any task, without repercussion or penalty.
Time Involvement	You will be required to complete the study over two days, taking approximately 2 hours on day one and 5 hours on day two.
Anonymity	Participants will be assigned a unique alpha-numeric code as a means of reference to their data. Data will be presented in averages across all measures in an effort to maintain confidentiality No information that could be used to infer the identity of the individual participants will be published. Video, photo or 3D scan image data will be retained for data analysis purposes and select images may be retained for archival purposes to inform future methodology development. These images will be stored on a password protected hard drive and will only be accessible by study investigators. Imagery that has been analyzed and not selected for archiving will be securely deleted from storage. The use of video or imagery for publications or presentation will only be considered where explicit permission is granted, as indicated by the participant in the DRDC Photo/Image Release Form.

Confidentiality	The confidentiality of your responses is guaranteed. Defence Research and Development Canadaresearchers are guided by, and adhere to, professional and ethical guidelines concerning behavioral research that involves people. Only DRDC personnel will have access to the information from this study. Unless explicit permission is provided by the participant, photographic or video imagery will only be available to qualified personnel for data analysis. If permission of use is granted, image use will be restricted to DND authorized publications and presentations.
Risks and Mitigation	Many common diving risks will unlikely be encountered due to the shallow depth of the static dive tank, as well for its controlled environment. This includes: barotrauma, decompression illness, hypothermia, and nitrogen narcosis. The risk of oxygen toxicity, hypercapnia, hypoxia, and drowning are still possible dangers of diving in the static tank. Despite these risks, they seldom occur due to the extensive education, training, and procedures enforced within diving operations. Qualified military and professional divers are aware and thoroughly knowledgeable of the signs and symptoms of the aforementioned risks. It is possible to develop an infection if equipment and ensembles are shared. This will be avoided by ensuring each participant dives in their own designated suits and all equipment is cleaned after use. Cramping of the hands due to the repetitive fine motor tasks may be an associated risk. These tasks will be short in duration and participants will be able to relax or stretch in between set ups for the next given task. Minor fatigue may be encountered after the repetitive gross motor task that involves swimming with a weight. The total swimming distance and amount of weight carried will not be strenuous, especially for these well trained CAF divers. This same risk applies for the FOV task, although swimming distances are not remarkable. Fatigue could also arise after the ROM measures since they will be required to control their buoyancy and movement throughout all motions. Weighted boots will be provided to assist participants with buoyancy control and to avoid unnecessary energy expenditure during this simple measure. Strains are a plausible risk during any of the ROM measures. All participants will be instructed on proper form and technique for each of the movements preceding data collection. Participants will also receive guidance and correction throughout the test to ensure proper form is attained. Movements will be encouraged to reach its fullest range without applying severe strain.

	Possible risks to the participant include minor skin irritation due to skin cleaning and landmarking. The lasers used in this experiment are classified as Class 1B and manufactured in compliance with the regulations of the Food and Drug Administration (United States Department of Health and Human Services), pertaining to laser safety. Maximum permissible exposure (MPE) for eyes or skin will not be exceeded throughout the course of the experiment.
Benefits	This study will provide preliminary data for future studies evaluating the relationship between encumbrance and task performance in diving operations. The benefit to the participant is the potential development of less constraining ensembles to permit additional safety and work efficiency.
Contact Information	For any further questions or concerns about this project, or if you wish a copy of the final report, please contact Mr. Allan Keefe; email: allan.keefe@drdc-rddc.gc.ca This project has been reviewed and approved by the DRDC Human Research Ethics Committee (Protocol 2015-005). If you would like to speak with the Chair of this Board, please contact: Chair, DRDC Human Research Ethics Committee (HREC); Phone number: 416-635-2098; or HREC-CEESH-Toronto@drdc-rddc.gc.ca

Annex B NASA TLX and Encumbrance rating questionnaires

The following questionnaires were presented to all participants after completion of each of the three underwater task conditions to evaluate subjective ratings of physical and cognitive workload and the effect of suit encumbrance on task performance.



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

Figure B.1: *NASA Task Load Index (TLX).*

Table B.1: *Subjective rating questionnaire on the effect of encumbrance on task performance.*

Question	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
	1	**2**	**3**	**4**	**5**
1. The suit felt overly restrictive/bulky and diminished my ability to move through simple ranges of motion.					
2. The suit design was restrictive/bulky and prevented me from performing fine motor tasks (e.g. nuts and bolts, rope tying) optimally.					
3. I had difficulty performing the "gross motor-transfer" task due to the suits restrictive fit.					
4. I had difficulty performing the "gross motor-transfer" task due to the suits configuration of bulk.					
5. As a means to compensate for a restricted field of view while wearing the AGA mask, large head or body movements were needed in this suit.					
6. My "In water- field of view" performance could have improved if the restrictiveness of the suit were to be minimized.					
7. My comfort was affected in this suit due to its restrictiveness and the configuration of bulk.					

Question	Strongly Disagree	Disagree	Undecided	Agree	Strongly Agree
	1	**2**	**3**	**4**	**5**
8. Working carefully with small objects in front of me was difficult and thus my fine motor performance was jeopardized due to the suits restrictiveness.					
9. Maintaining a static position while working carefully with small objects was difficult.					
10. The level of bulk and restrictiveness in this suit did not affect my functional task performance.					

Annex C Summary of DCIM/DRDC – Sponsored reports on the Human Factors of Mine Counter Measures Operations

The following is a summary of Mine Counter Measures Human Factors reports produced for DCIEM/DRDC's Experimental Diving Unit by Shearwater Engineering from 1997 to 2006.

OPTIMIZING THE PERFORMANCE AND SAFETY OF MINE COUNTER-MEASURES DIVING

Phase 1

Morrison, J., Hamilton, K. and Zander, J. 1997. Optimizing the performance and safety of mine countermeasures diving. Phase 1 Report. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-5-7266; 210 pp, DCIEM Report 97-CR-43

Phase 2

Morrison, J., Hamilton, K. and Zander, J. 1998. Optimizing the performance and safety of mine countermeasures diving. Phase 2, Part1 Report. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-5-7266; 33 pp, DRDC CR 2000-003

Morrison, J., Zander, J. and Hamilton, K. 1998. Optimizing the performance and safety of mine countermeasures diving. Phase 2, part2: Information and display requirements for MCM Diving. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-5-7266; 35 pp, DRDC CR 2000-004

Morrison, J., Zander, J. and Hamilton, K. 1999. Optimizing the performance and safety of mine countermeasures diving. Phase 2, part 3 Report. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-5-7266; 68 pp DRDC CR 2000-005.

Phase 3

Morrison, J.B. and Zander, J.K. 2005. Factors influencing manual performance in cold water diving. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 37 pp

Morrison, JB. and Zander, J.K. 2005. Determining the appropriate font size, and use of colour and contrast for underwater displays. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 48 pp

Morrison, JB. and Zander, J.K. 2005. Evaluation of head mounted and head down information displays during simulated mine-countermeasures dives to 42 msw. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 52 pp

Morrison, J.B. and Zander, J.K. 2005. Investigation of button size and spacing for underwater controls. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 26 pp

Morrison, J.B. and Zander, J.K. 2005. Investigating the usability of underwater communications systems. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 26 pp

Morrison, J.B. and Zander, J.K. 2005. The effect of pressure and time on information recall. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 27 pp

Morrison, J.B. and Zander, J.K. 2005. The effects of exposure time, pressure and cold on hand skin temperature and manual performance when wearing 3-fingered gloves. Prepared by Shearwater Human Engineering for: Department of National Defence PWGSC Contract No. WW7711-997606; 26 pp

PUBLICATIONS:

Ph.D. THESIS

Zander, J. 2005 Ergonomic guidelines for communication and display of information during mine counter-measures diving operations. Ph.D., Simon Fraser University.

CONFERENCES (FULL PROCEEDINGS PUBLISHED)

Morrison, J.B. and Zander, J.K. 2005. Evaluation of the manual performance capabilities of workers wearing protective gloves. 36th Annual Conference, Association of Canadian Ergonomists, August 2005, Halifax, NS

Morrison, J.B., Zander, J.K. and Cooper, J B. 2006. Investigation of the usability of diver underwater communications systems. Proc. 37th Annual Conference, Association of Canadian Ergonomists, October 2006, Banff, AL

INTERNATIONAL ERGONOMICS ASSOCIATION (IEA) K.U. SMITH STUDENT AWARD

Zander, J.K. 2006. Development and evaluation of ergonomic design guidelines for underwater displays. International Ergonomics Association XVIth Triennial Congress, July 10-14, 2006, Maastricht, Netherlands.

ABSTRACTED CONFERENCE PUBLICATIONS

Morrison, J.B., and Zander, J.K., 2003. Optimizing the performance and safety of mine countermeasures diving. Undersea and Hyperbaric Medical Society Annual Scientific Meeting, Quebec, Quebec, June 19-21, 2003.

Zander, J.K. and Morrison, J.B. 2003. The effects of neoprene gloves, pressure and cold water on manual performance of divers. Undersea and Hyperbaric Medical Society Annual Scientific Meeting, Quebec, Quebec, June 19-21, 2003.

Zander, J.K. and Morrison, J.B. 2004. The Effects of Cold, Pressure and Gloves on Manual Performance Capabilities of MCM Divers. Canadian Association of Underwater Scientists, Annual Meeting, October 21-24, University of British Columbia, Vancouver, BC

Zander JK, and Morrison J.B. 2005. Effects of exposure time, pressure and cold on hand skin temperature and manual performance when wearing 3-fingered neoprene gloves. Undersea and Hyperbaric Medical Society Annual Scientific Meeting, , Las Vegas, Nevada.

Zander J.K. Morrison J.B. and Eaton D. 2005. Evaluation of head mounted and head down information displays during simulated mine countermeasures dives to 42 msw. Undersea and Hyperbaric Medical Society Annual Scientific Meeting, Las Vegas, Nevada.

List of symbols/abbreviations/acronyms/initialisms

2D, 3D	Two, Three Dimension
BDR	Battle Damage Repair
CABA	Compressed Air Breathing Apparatus
CAF	Canadian Armed Forces
CETTs	Comprehensive Ergonomics-based Tools and Techniques
CFAS	Canadian Forces Anthropometric Survey
CFEME	Canadian Forces Environmental Medicine Establishment
CROM	Cervical Range of Motion
DND	Department of National Defence
DRDC	Defence Research and Development Canada
DSTKIM	Director Science and Technology Knowledge and Information Management
EDUG	Experimental Diving Undersea Group DV Dependent Variable
EOD	Explosive Ordnance Disposal
FOV	Field of View
FP	Force Protection
HFPP	Human Factors Program Plan
HFTP	Human Factors Test Plan
HUET	Helicopter Underwater Escape Training
IV	Independent Variable
LED	Light Emitting Diode
MAST	Marine Aviation Survival Training
MCM	Mine Counter Measures
PPE	Personal Protection Equipment
RCN	Royal Canadian Navy
ROM	Range of Motion
SOLAS	Safety of Life at Sea

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Defining the relationship between encumbered ensembles and task performance in diving operations: A pilot study

4. AUTHORS (Last name, followed by initials – ranks, titles, etc. not to be used. Use semi-colon as delimiter)

Keefe, A.; Lim, T.

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12. KEYWORDS, DESCRIPTORS or IDENTIFIERS (Use semi-colon as a delimiter.)

Diving; task performance; Comprehensive Ergonomics Tools and Techniques (CETTs); ergonomics ; encumbrance

13. ABSTRACT/RÉSUMÉ (When available in the document, the French version of the abstract must be included here.)

DRDC's Experimental Diving and Undersea Group (EDU) recognizes the requirement for a capability to perform sound human factors and ergonomic research to support the specification, design, development, and evaluation of diving clothing, equipment and platforms. In order to leverage the emerging tools and capabilities available through DRDC's Comprehensive Ergonomics-based Tools and Techniques (CETTs) capabilities, a pilot study was conducted to evaluate the effect of ensemble encumbrance on diver underwater task performance.

Five Royal Canadian Navy Reserve divers were recruited from the HMCS York to participate in this study. Each diver participated in three dive encumbrance conditions consisting of either a a) 6mm thick wetsuit, b) Fusion dry suit or c) Kodiak dry suit. An AGA full face dive mask and Compressed Air Breathing Apparatus (CABA) tanks were worn in each condition. Dive ensemble encumbrance was quantified by obtaining 3D volumetric scans, and measuring field of view and cervical range of motion. In-water assessment of ensemble encumbrance consisted of whole-body range of motion activities.

Performance tasks were based on simulated mine counter measures tasks and consisted of fine motor (rope tying and nuts/bolts assembly), gross motor (weight transfer) and a visual search tasks. All in-water tasks were recorded using waterproof GoPro™ cameras and evaluated according to time to task completion, NASA TLX response and subjective questionnaire. Despite the low number of participants, results indicated trends that were consistent with task performance being adversely affected by encumbrance, as defined by a reduced range of motion. The exception was the nuts and bolts task which appeared to benefit by the extra stability provided by a more restrictive suit. This research reinforces the importance of identifying objective measures of encumbrance that are relevant to diver task performance. Challenges to quantifying dive ensemble encumbrance in an underwater environment are identified and research gaps, tools, resources and facilities to support advanced diving human factors research are identified.

ABSTRACT/RÉSUMÉ (When available in the document, the French version of the abstract must be included here.)

Le Groupe de l'unité de plongée expérimentale (GPE) de RDDC reconnaît la nécessité de posséder la capacité d'effectuer des recherches approfondies sur les facteurs humains et l'ergonomie pour appuyer la description, la conception, la mise au point et l'évaluation des vêtements, de l'équipement et des plateformes de plongée. Afin de tirer profit des capacités et des outils émergents qu'offre l'ensemble exhaustif d'outils et de techniques ergonomiques (EEOTE) de RDDC, on a mené une étude pilote dans le but d'évaluer l'effet de la charge exercée par l'équipement sur l'efficacité des tâches effectuées sous l'eau par les plongeurs

On a recruté cinq plongeurs de la Marine royale canadienne (Réserve) parmi l'équipage du NCSM York pour participer à l'étude. Chaque plongeur a pris part à trois exercices selon différentes charges de plongée, à savoir : a) une combinaison humide de 6 mm; b) une combinaison étanche Fusion; c) une combinaison étanche Kodiak. Tous les plongeurs étaient équipés d'un masque facial intégral AGA et des bouteilles de plongée d'un appareil respiratoire à air comprimé (ARAC) lors de chaque exercice. La charge selon l'équipement de plongée a été quantifiée au moyen de balayages volumétriques et en mesurant le champ visuel et l'amplitude de mouvement cervical. L'évaluation sous l'eau comportait des exercices de mouvement d'amplitude de tout le corps.

L'exécution des tâches consistait en une simulation d'exercices de lutte contre les mines et comportait des activités de motricité fine (nouage de cordes et assemblage par boulons et écrous), de motricité globale (transfert du poids) et de recherche visuelle. Toutes les tâches sous l'eau ont été enregistrées au moyen de caméras étanches GoPro™ et évaluées en fonction du délai pour les mener à bien, de l'indice de charge de travail (ICT) de la NASA et d'un questionnaire subjectif. Malgré le nombre peu élevé de participants, les résultats ont montré des tendances qui correspondaient à l'efficacité des tâches sur lesquelles la charge exerce une influence défavorable, comme l'indique une amplitude de mouvement réduite. L'exception étant l'assemblage par boulons et écrous, celui-ci a semblé profiter d'une plus grande stabilité qu'apportait une combinaison plus contraignante. L'étude confirme l'importance d'établir des mesures objectives pour évaluer la charge pouvant avoir une incidence sur l'efficacité du travail des plongeurs. On a souligné la difficulté de déterminer la charge globale de l'équipement de plongée dans un environnement sous-marin, ainsi que les lacunes sur le plan de la recherche, des outils, des ressources et des installations pour appuyer des recherches approfondies sur les facteurs humains relatifs à la plongée.