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A fishermen-developed intervention reduced musculoskeletal load associated with commercial Dungeness crab harvesting

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ABSTRACT

This study characterized physical risk factors associated with injuries during a Dungeness crab harvesting task and evaluated the efficacy of a fishermen-developed ergonomic control (banger bar) in mitigating physical risk factors, including biomechanical loads in the low back, shoulders, and upper extremities, and postural instability. In a repeated-measures laboratory study, 25 healthy male participants performed manual crab harvesting tasks in five conditions: without any banger bar (control) and with 4 bars of differing heights or designs. The results showed that the ergonomic control reduced trunk and shoulder angles, L5/S1, and shoulder moments; muscle activities in low back, shoulders, and upper extremities; perceived exertion ratings; and postural sway measures. Moreover, these measures were lowest when the bar height was at 60 cm, indicating that the banger bar can reduce the risk of musculoskeletal injuries and postural instability, and that bar height is an important factor affecting these injury risk measures.

1. Introduction

The West Coast (Pacific) Dungeness crab fishery is one of the region's most valuable fisheries. For example, in Oregon it is the most valuable single species commercial fishery, harvesting an average of 16 million pounds per season over a 25-year period (Oregon Department of Fish and Wildlife, 2021). Currently, Oregon issues 315 vessel permits for Dungeness crab each year, Washington issues 228 Coastal permits and 248 permits in Puget Sound, and California issues around 500 permits (California Department of Fish & Wildlife, 2022; Oregon Department of Fish & Wildlife, 2021; Washington Department of Fish and Wildlife, 2022). Additionally, the most recent data available show that approximately 3200 captains and deckhands comprise the fleet of the West Coast Dungeness crab fishery (Hughes et al., 2013).

However, the West Coast Dungeness crab fleet is also one of the highest-risk commercial fishing fleets in the United States (US), with vessel disasters and falls overboard recognized as major contributing factors in worker fatalities (Lincoln and Lucas, 2008, 2010; Syron et al., 2017). According to the National Institute for Occupational Safety and Health (NIOSH) Commercial Fishing Incident Database (CFID), which facilitates collection of fatality data to identify high-risk fisheries, the fatality rate of workers in the fleet ranked third nationally, with 310 deaths per 100,000 full-time equivalent fishermen from 2000 to 2009 (Lincoln and Lucas, 2010). Ongoing projects with the United States Coast Guard (USCG) and NIOSH are focused on preventing fatalities caused by vessel disasters (Lincoln and Lucas, 2008, 2010; Syron et al., 2017).

While continued attention is clearly needed to reduce the fatality risk, non-fatal injuries, which can range from less severe to work limiting to disability, must also be addressed. The Fishermen Led Injury Prevention Program (FLIPP) showed that non-fatal injuries are also highly prevalent among commercial fishermen (Bovbjerg et al., 2019; Case et al., 2015; Kincl et al., 2019). FLIPP results for Dungeness crab fishermen showed that the majority of limiting nonfatal injuries (88%) occurred with deckhands and that the most common injuries were sprains and strains (36%). Most of these injuries were associated with handling, hauling, and setting crab pots (72%) (FLIPP Survey Results, 2017). These gear-handling activities can pose forceful exertions, awkward postures, and repetitive motions. Moreover, these physical risk factors could impact the postural stability of fishermen as muscular fatigue and awkward trunk postures can negatively affect postural stability (Davidson et al., 2004, 2009; Granata et al., 2004; Granata and Gottipati, 2008; Granata and Wilson, 2001; Hendershot et al., 2013; Larson and Brown, 2018; Lin et al., 2009; Pline et al., 2006; Vuillerme et al., 2007; Wilson et al., 2006). This may lead to an increase in the risk of falls (Davidson et al., 2004; Pline et al., 2006) and potentially falls

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overboard, which are a major source of fatal injuries in commercial fishing. Despite these potential hazards, there has been a lack of studies to objectively quantify the physical injury risk factors and postural stability associated with commercial Dungeness crab harvesting. While there has been a few ergonomic studies of commercial crab pot and gill net fishing activities on the east coast, these studies relied on observational methods and video footage (Kucera et al., 2008; Mirka et al., 2005) which could be more prone to biases than objective assessment methods. Although one study evaluated the use of a crab pot ramp and boom on the side of fishing vessels (for pulling up and emptying pots) using objective assessment tools in a laboratory setting (Mirka et al., 2011), the natures of the tasks and interventions assessed in that study are significantly different from our targeted tasks and intervention for Dungeness crab harvesting. Therefore, the first aim of this study was to objectively quantify the biomechanical load and postural stability during the current crab pot handing activity.

Moreover, direct feedback from fishermen and community researchers, as well as the FLIPP study outreach, provided an idea for an ergonomic control to reduce the physical risk factors related to handling crab pots. This fishermen-designed control, referred to as a “banger bar”, adds padding and a stop bar to the sorting table so that a retrieved pot can be tipped and banged against to release the crab. This reduces the

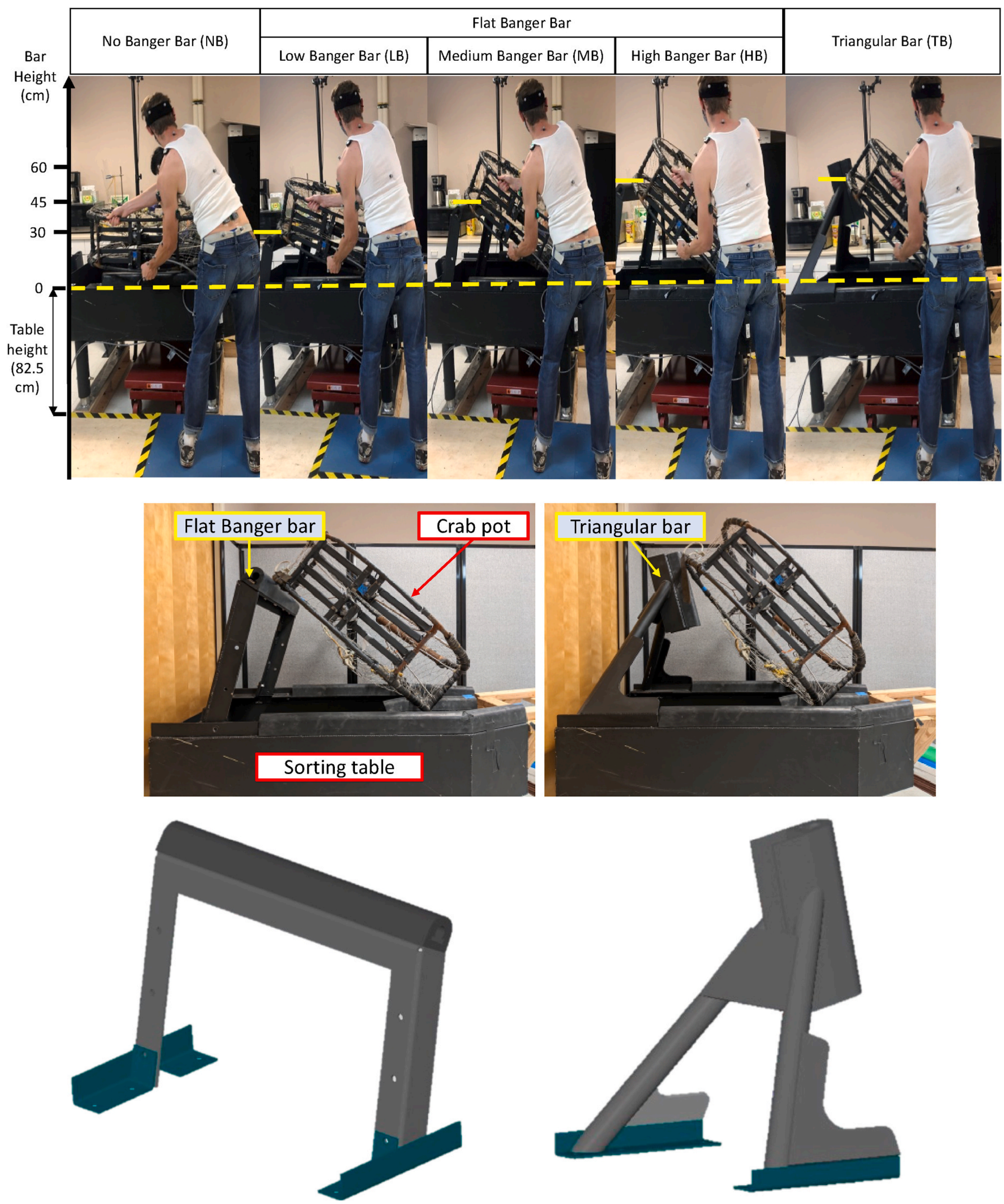

Fig. 1. Experimental conditions and setup with a crab sorting table, crab pot, and a participant performing the crab pot handling task with five banger bar conditions: no bar (NB), a flat bar with three different heights (LB – 30, MB – 45, HB – 60 cm), and a triangular bar (TB – 60 cm in height).

distance the crab pot must travel and the force exerted by the fishermen in order to empty the contents of the pot into the sorting table. Potential primary benefits of using the control include reduction of awkward postures, forceful exertions, and repetitive motions. Additionally, this control could potentially improve postural stability by reducing awkward lower back postures and musculoskeletal fatigue caused by the aforementioned physical risk factors.

During our field-study, a newly-designed banger bar was identified on a newer vessel (Fig. 1). This triangular banger bar can potentially reduce pinch point hazards because it has only a single point of contact for the pot that is away from the hands of the fishermen compared to the flat bar that has two contact points. Despite the potential benefits of the banger bars, there has been no scientific evidence on the effects of the banger bar and their designs on physical injury risks and postural stability during Dungeness crab pot handling. Therefore, the second study aim was to determine whether a banger bar would reduce biomechanical load and postural instability during Dungeness crab pot handing and whether such effects would differ between two banger bar designs (flat vs. triangular).

2. Methods

2.1. Participants

Twenty-five healthy adults were recruited for this laboratory-based study via email solicitation and printed flyers throughout the Oregon State University in Corvallis, OR, and commercial fishermen community in Newport, OR. While outreach efforts were made to recruit from the local commercial fishermen community, none of the participants were Dungeness crab fishermen or had experience working in commercial fishing. The mean (standard deviation) age, weight, and height were 31.3 (10.0) years, 81.4 (11.5) kg, and 179.7 (5.7) cm. Only male participants were recruited based on our recent study with over 400 Dungeness crab fishermen revealed the majority of the crab fishermen were in fact males. The inclusion criteria for participants were: 1) no restriction in physical activity; 2) no musculoskeletal pain in the low back, shoulder, and upper extremity regions for the past 7 days; 3) no current medication related to musculoskeletal disorders; and 4) no visual or vestibular deficits that may influence normal balance control. These inclusion criteria were formulated to avoid potential risk of injury during manual material handling activities.

2.2. Experimental setup

To create a realistic experimental setup, we collected the dimensions of various crab sorting tables (height, width, and length), crab pots (diameter, height, and weight), and banger bars (height and length) from 13 commercial Dungeness fishing vessels in Oregon and Washington (Kim et al., 2022). Based on these field data, a crab sorting table and banger bar were manufactured by a coastal vessel equipment fabricator, who works with regional commercial fishermen to outfit their vessels. The fabricated table dimensions were 82.5 (height) x 94.0 (width) x 152.4 (length) cm. Five different banger bar conditions were determined based on the field data (Kim et al., 2022) to reflect designs and configurations used by the commercial fishermen: no bar, a flat bar with three different heights (30, 45, and 60 cm), and a triangular bar (height: 60 cm) (Fig. 1).

The crab pot for this study, which was previously used in commercial crab fishing, had a diameter of 107 cm and a mass of 40 kg. To minimize potential interference with other experimental equipment for this study, the pot was empty rather than having crab, bait, weights, or other gear required for fishing. To measure the 3-D hand force, two load cells were

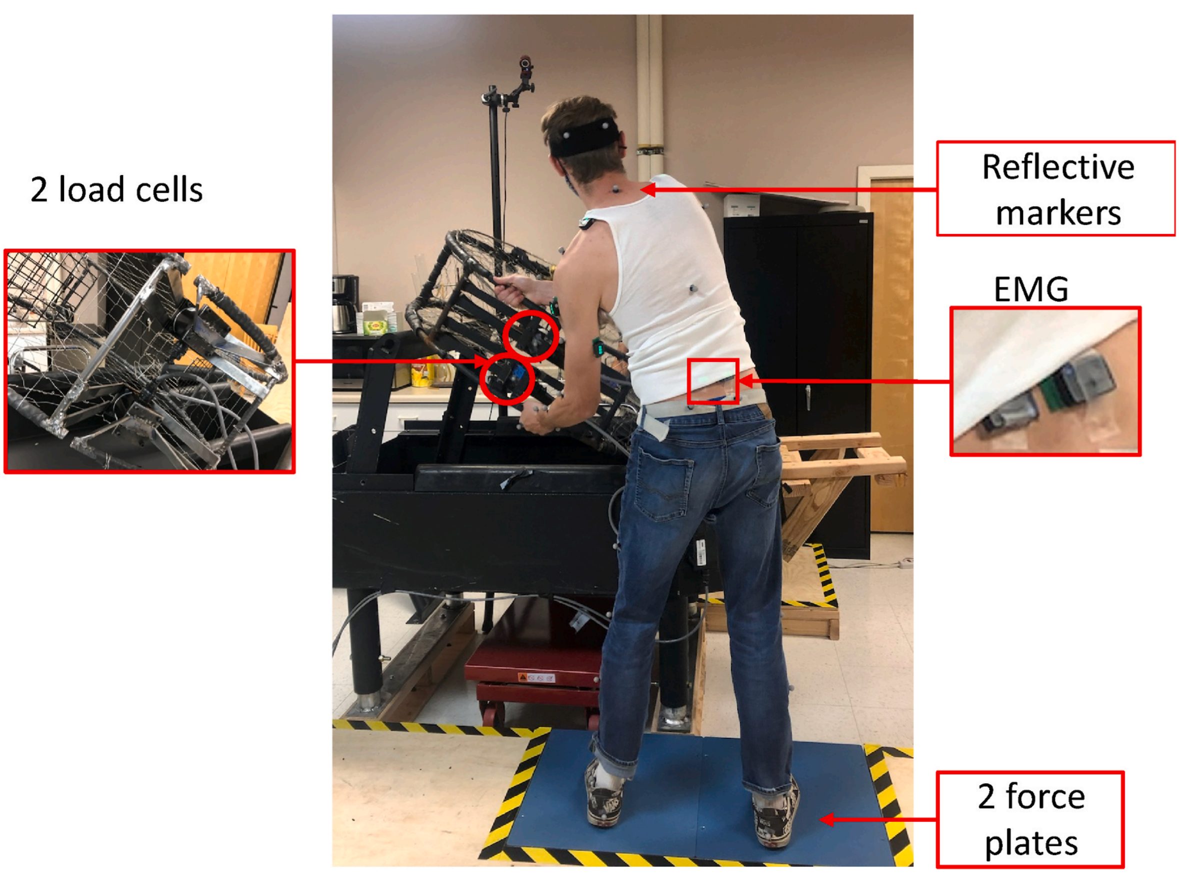

Fig. 2. Experimental apparatus: 2 load cells to measures 3-D hand force; 39 reflective markers to collect whole-body kinematic data; electromyography (EMG) to measure muscle activity in erector spinae, trapezius, anterior deltoid, middle deltoid, triceps, and biceps; 2 force plates to measure postural stability.

embedded to the crab pot with custom-built brackets that were welded to the crab pot rims (Fig. 2). This attachment allowed the participants to grab and handle the crab pot in a way that commercial fishermen would normally do. The experimental set up and pot handling were validated by three commercial Dungeness crab fishermen and a local fabricator who confirmed that the setup and handling reflect their manual crab pot handling activity.

2.3. Experimental protocol

Prior to the experiment, all the participants were briefed on the study objectives, procedures, equipment, tasks, potential risks, and anticipated benefits of the study. After giving a written consent, reflective markers and electromyography electrodes were placed on participants. Each participant was given sufficient practice time to get familiarized with the task and experimental setup, which lasted until they were able to perform the task correctly and they verbally confirmed their ability and familiarity with the task and setup.

The task consisted of grabbing the pot with both hands, after a verbal signal to start, then tilting the pot from its vertical standing position to bang it against the banger bar or surface of the table, depending on the condition (Fig. 1). Immediately afterwards, the pot is tilted back to its original standing position and letting go of the pot, which marks the end of the task. Each crab pot handling task lasted 3–5 s, and the task was repeated three times for each of the five conditions. The participants were directed to perform the task at a consistent speed across all the trials with the researchers' verbal signals. Because crab pot handling is a two-person job, all participants always completed the task on the same side with the same "deckhand" (a member of the study team) on the opposite side of the pot, so pots were always tilted to the participant's left. Three commercial Dungeness crab fishermen were invited to the laboratory to confirm that the task and pot handling methods reflected actual crab pot handling activities.

The order of the experimental conditions was randomized and counterbalanced to minimize potential confounding effects from the experimental order. Five-minute breaks were given between conditions to minimize the residual fatigue effects of the previous condition. During each task, angle, moment, and muscle activity (in the low back, shoulders, and upper extremities), postural stability, and perceived exertion ratings were measured (Fig. 2). Before and after each condition, the participants completed the self-reported whole-body (Borg RPE) and localized exertion (Borg CR-10) questionnaires. The experimental protocol was approved by the University's Institutional Review Board (IRB) (Protocol number: IRB-2019-0318).

2.4. Outcome measures

2.4.1. Angle and moment

Angles and moments about the low back and shoulders were measured using the kinematic and kinetic data collected by a three-dimensional (3-D) optical motion capture system (Flex 13; Optitrack; Natural Point, OR) and two six-degree-of-freedom load cells (PY6; Bertec; Columbus, OH) during the tasks (Fig. 2). A total of 39 reflective markers were placed on the head, upper and lower arms, hands, trunk, pelvis, upper and lower legs, and feet of participants based on the full body biomechanics marker set from an optical motion capture software program (Motive 2.0; Optitrack; Natural Point, OR). In addition, six reflective markers were placed on the two load cells to estimate the location and force vector of 3-D hand force. Using the 8-camera optical motion capture system, the positions of the reflected markers were collected at a sample rate of 120 Hz. Simultaneously, the 3-D hand force was bilaterally measured using two load cells at 1000 Hz. The raw kinematic and kinetic data were filtered by a digital zero-phase 4th order Butterworth filter with a cutoff frequency of 6 Hz (Motive 2.0; Optitrack; Natural Point, OR) and 10 Hz (Visual3D; C-Motion Inc., Germantown, MD), respectively.

Based on the filtered kinematic data, trunk flexion and lateral bending angles to the left and the shoulders' flexion and abduction angles were calculated using a biomechanics analysis software (Visual3D; C-Motion Inc., Germantown, MD). The L5/S1 (lumbosacral joint) flexion and lateral bending moments to the left, along with the shoulders' flexion and abduction moments were computed using a 3-D dynamic multi-segment model (Hwang et al., 2019; Kingma et al., 1996). Body segment inertial parameters were estimated using a regression model incorporating each participant's anthropometry (de Leva, 1996). A top-down approach was used to calculate moments based on the collected 3-D external hand force, estimated body segment inertial parameters, and their respective moment arms estimated from kinematic data (Faber et al., 2020; Iino and Kojima, 2012). Subsequently, the peak (95th percentile) angles and moments were calculated.

2.4.2. Muscle activity

Muscle activities in the low back, shoulders, and upper extremities were measured at 1000 Hz using a 16-channel wireless data logger (Trigno Avanti; Delsys; Natick, MA). Muscle activity data were collected bilaterally in six muscle sites: 1) erector spinae, 2) trapezius, 3) anterior deltoid, 4) middle deltoid, 5) triceps, and 6) biceps. These muscles were selected because they are considered the major muscles responsible for manual handling activities (e.g., loading/unloading) similar to crab pot handling (Hwang et al., 2017; Rashedi et al., 2014; Weston et al., 2018). Skin preparation, muscle identification, and electrode placement were performed according to the European Recommendation for Surface Electromyography (EMG) (Hermens et al., 2000). For normalizing the EMG data, the sub-maximal reference voluntary contractions (RVC) from the erector spinae and the maximum voluntary contractions (MVC) from the trapezius, anterior deltoid, middle deltoid, triceps, and biceps were collected according to previous studies (Boettcher et al., 2008; Marras and Mirka, 1993). The sub-maximal RVCs were chosen to avoid any potential back injuries as the low back is susceptible to injuries. Erector spinae RVCs were collected during 30° trunk forward flexion without any external resistance (Hwang et al., 2019). Upper trapezius, anterior deltoid, and middle deltoid MVCs were obtained during three tasks: (a) scapular elevation, (b) 90° shoulder abduction in the scapula plane with internal humeral rotation and extended elbow, and (c) 125° shoulder flexion against manual resistance (Boettcher et al., 2008). Triceps and biceps MVCs were obtained during elbow extension and flexion starting from 90° elbow flexion against manual resistance, respectively (Roman-Liu and Bartuzi, 2018). Each contraction lasted 3 s and were repeated three times with 2-min breaks between contractions (Soderberg and Knutson, 2000). The raw EMG data (collected during both the experimental sessions and RVC/MVC) were bandpass filtered (20–400 Hz) and rectified using the root mean square (RMS) average with a 125-ms moving window (EMGworks; Delsys; Natick, MA). The maximal RMS values of RVCs or MVCs were used to normalize the EMG data (%RVC and %MVC). The normalized EMG data were summarized with the peak (90th percentile) values for subsequent statistical analyses.

2.4.3. Postural stability

To evaluate postural stability during the tasks, tri-axial ground reaction forces and moments were sampled at 1000 Hz using two force platforms (AMTI BMS464508-2K-SYS, Watertown, MA, USA). The force platforms were positioned and mounted where the commercial fishermen would normally place their feet to reflect most realistic crab pot handling activities in a laboratory setting. The force plate data were low-pass filtered (4th order, zero-phase-lag, Butterworth, 10 Hz cut-off frequency) and transformed to obtain center of pressure (COP) values (Davidson et al., 2004). COP-based sway measures, including median power frequency, mean velocity, root mean square (RMS) distance, and COP sway area, were derived from the COP trajectories according to procedures described in previous studies (Lin et al., 2008; Prieto et al., 1996).

2.4.4. Perceived exertion

Borg's rating of perceived exertion (RPE) scale was used to quantify the whole-body exertion on a scale of 6 (very, very light) to 20 (very, very hard) (Borg, 1970). Localized perceived exertion in the low back and shoulders was collected using the Borg category ratio (CR-10) scale of 0 (rest) to 10 (maximal) (Borg, 1982). The verbal anchors were provided in both Borg RPE and CR-10 scales.

2.5. Statistical analysis

Generalized linear mixed models (GLMM) were used to determine the effects of the ergonomic control (banger bar) on the corresponding dependent variables (trunk and shoulder angles, L5/S1 and shoulder moments, normalized muscle activities in low back, shoulders, and upper extremities, postural stability, and perceived exertion). The fixed effect was the banger bar condition (5 levels: no bar, low bar, medium bar, high bar, and triangular bar). Random intercepts were introduced to account for within-subject correlations. All the dependent variables followed normal distributions except for muscle activity and postural stability measures, which were highly skewed. Therefore, muscle activity and postural stability data were transformed with logarithm. An alpha (Type I) error of 0.05 was used as a statistical significance threshold. Any statistical significance was followed up with Tukey's HSD post-hoc tests. The JMP software (Pro 15; SAS Institute; Cry, SC) and R programing language (R 4.1.1, R Core Team; Vienna, Austria) were used for the statistical analysis.

3. Results

3.1. Trunk angle and L5/S1 moment

The trunk angle data showed that the crab pot handling tasks posed substantial lateral bending (up to ~43°), which was much greater than the measured flexion angles (up to ~10°) (Fig. 3-a). The trunk flexion and lateral bending angles during the crab pot handling tasks were significantly affected by the banger bar conditions. With banger bars, the trunk flexion and lateral bending angles were consistently lower (~27–60%) than without the bars ($p < 0.0001$), and the angle measures decreased as the bar height increased.

L5/S1 flexion and lateral bending moments were also significantly affected by the banger bar conditions (Fig. 3-b). The peak L5/S1 moments were lower (~5–64%) with the banger bars as compared to the no-bar condition. Furthermore, as the bar height increased, L5/S1 flexion and lateral bending moments decreased. The post-hoc comparisons showed that the high and triangular bars, which both had a height of 60 cm, resulted in smaller peak flexion moments about the L5/S1 than no and low (30 cm) bar conditions ($p < 0.003$). Similarly, the peak lateral bending moments about the L5/S1 were lower with the high and triangular bars than with the other conditions ($p < 0.002$).

3.2. Shoulder angle and moment

The shoulder angle data demonstrated that the crab pot handling tasks were associated with shoulder flexion (up to ~82°) and abduction (up to ~29°) (Fig. 4). When comparing the right and left shoulder angle measures, the right shoulder angles tended to be higher (up to ~40° flexion; up to ~17° abduction) than the corresponding left shoulder angles.

These shoulder flexion angle measures were significantly affected by the banger bar conditions. The right and left shoulder peak flexion angles were the highest without the bars ($p < 0.0001$) (Fig. 4). As the height of the bars increased, the shoulder flexion angles decreased. On the other hand, the shoulder abduction angles showed less consistent and smaller differences across the conditions compared to shoulder flexions angles although some of the differences reached statistical significance.

Similar to the shoulder angles, the shoulder moments were significantly different across the banger bar conditions (Fig. 5). The peak left shoulder flexion moments were significantly lower with the high and triangular bars compared to low and medium bar ($p < 0.02$) while no significant differences were found in the peak right shoulder flexion moments. The peak abduction moments for both shoulders decreased as the bar height increased with varying statistical significance.

3.3. Muscle activity

The peak low back muscle (erecter spinae) activity was significantly lower (up to ~92 and 67 %RVC in the right and left side, respectively) with the banger bars compared to the no-bar condition (Fig. 6). There was also a consistent trend showing that the low back muscle activity decreased as the bar height increased. In addition, the low back muscle activity in the right side was substantially higher (up to ~95 %RVC) than the left side.

The shoulder muscle (trapezius, anterior deltoid, and middle deltoid)

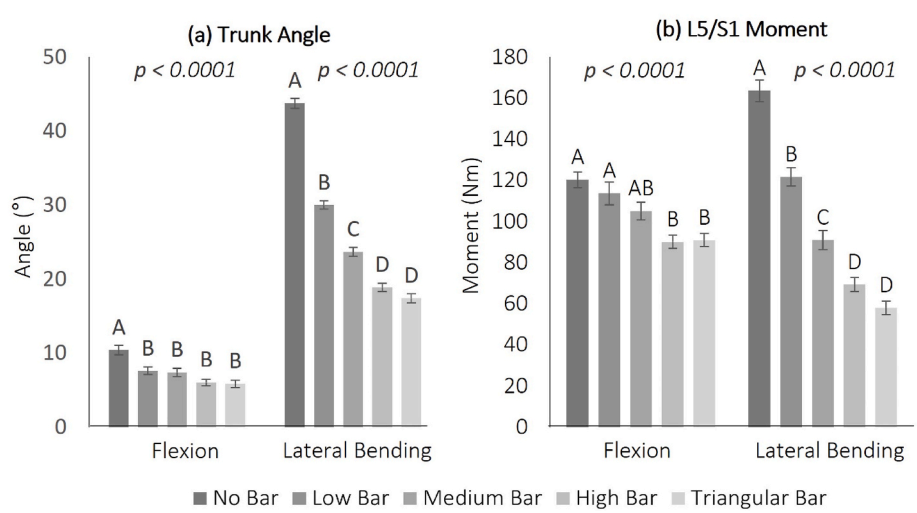

Fig. 3. Mean and standard error (indicated by error bars) of peak (95th percentile) (a) trunk angles and (b) L5/S1 moments during crab pot handling with five different banger bar conditions [N = 25]. P-values were calculated from mixed models with the banger bar condition (fixed effect) and the participant (random effect). Different superscript letters (A, B, C, and D) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests ($p < 0.05$).

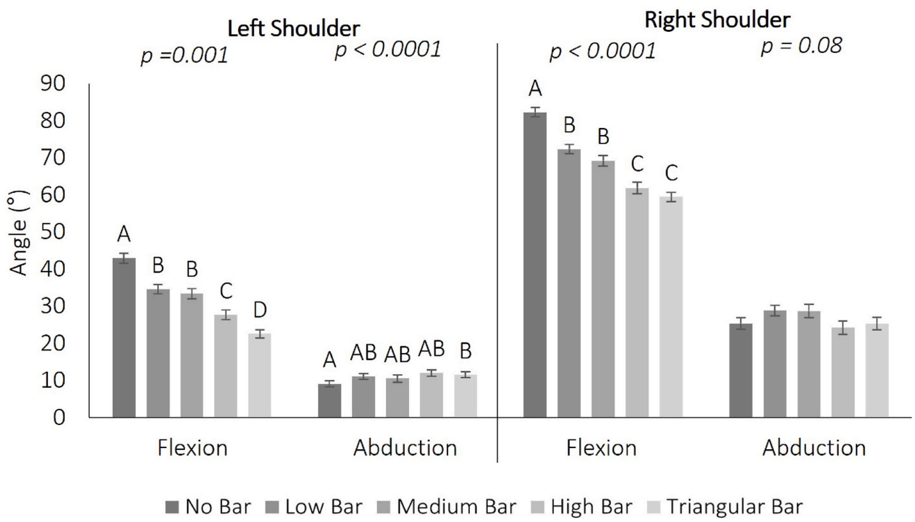

Fig. 4. Mean and standard error (indicated by error bars) of peak (95th percentile) left and right shoulders angles during crab pot handling with five different banger bar conditions [N = 25]. P-values were calculated from mixed models with the banger bar condition (fixed effect) and participant (random effect). Different superscript letters (A, B, C, and D) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests ($p < 0.05$).

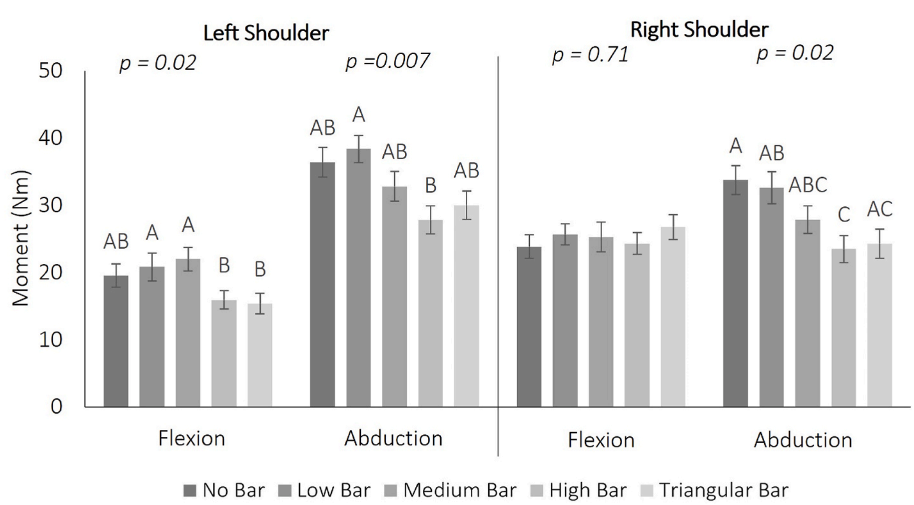

Fig. 5. Mean and standard errors (indicated by error bars) of peak (95th percentile) left and right shoulders moments during crab pot handling in five different banger bar conditions [N = 25]. P-values were calculated from mixed models with the banger bar condition (fixed effect) and participant (random effect). Different superscript letters (A, B, and C) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests ($p < 0.05$).

activities were also significantly affected by the banger bars (Fig. 6). In particular, the peak right trapezius muscle activity measures were significantly lower (up to ~22 %MVC) with the high and triangular bars than those with no and low bars. Similar to the low back muscle activity, the trapezius muscle activity decreased as the bar height increased. The right trapezius muscle activity was substantially higher (up to ~16 %MVC) than the left side. Moreover, the trapezius muscle activity without the banger bar showed substantial muscular load levels, especially on the right side (54.3 %MVC). Anterior and middle deltoid muscle activities tended to be lower with the banger bars compared to the no-bar condition. Specifically, the peak deltoid muscle activities in both sides were lower with the high and triangular bars than the no-bar and low-bar conditions. Moreover, the anterior deltoid muscle activity was significantly higher (up to ~19 %MVC) than the middle deltoid during the crab pot handling tasks, which was consistent with the shoulder angle measures (i.e., greater shoulder flexion than abduction).

The upper arm muscle (triceps and biceps) activities also showed a consistent trend that the upper arm muscle activity was lower with the banger bars (especially, the high and triangular bar) as compared to the no-bar condition. However, some of differences in the triceps and biceps muscle activity measures did not reach statistical significance (Fig. 6).

3.4. Perceived exertion

Both whole-body and localized perceived exertion measures were significantly impacted by the banger bar conditions (Fig. 7). The results showed that the whole-body and localized exertion measures were highest without the bar ($p < 0.04$). Moreover, the perceived exertion levels decreased as the bar height increased. When compared with the no-bar condition, the high and triangular bars reduced localized exertion in the low back and shoulders by up to 1 point on the 10-point scale (Borg CR-10).

3.5. Postural stability

Postural stability was significantly affected by the banger conditions (Table 1). The mean velocity and RMS displacement in both anterior-posterior (AP) and medial-lateral (ML) directions were highest with no

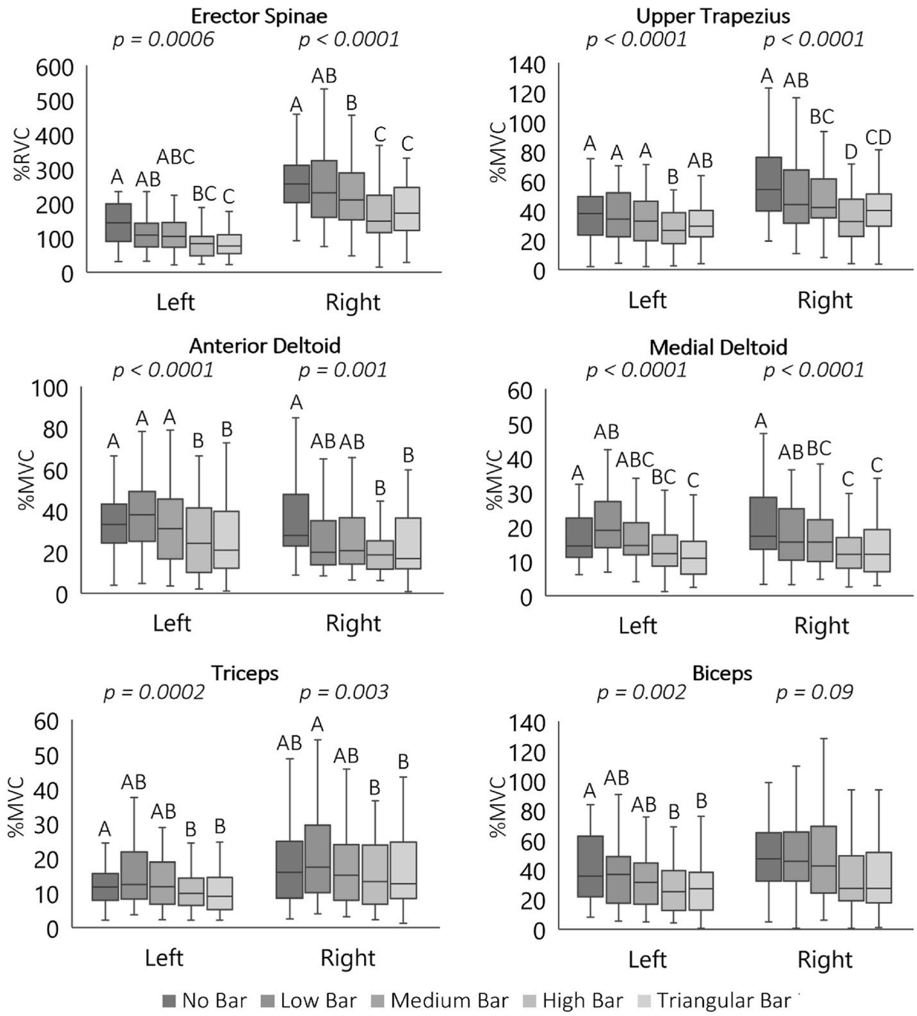

Fig. 6. Peak (90th percentile) muscle activity in left and right erector spinae [Reference voluntary contraction (%RVC)], trapezius, anterior deltoid, medial deltoid, triceps, and biceps [Maximum voluntary contraction (%MVC)] during crab pot handling in five different banger bar conditions [N = 25]. The boxes show interquartile ranges (IQR = 75th-25th percentile) ranges; the horizontal lines in the boxes show 50th %tile values; and the lower and higher whiskers are minimum and maximum values (25th percentile ± 1.5*IQR). P-values were calculated from mixed models with the banger bar condition (fixed effect) and the participant (random effect). Different superscript letters (A, B, C, and D) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests (*p < 0.05*).

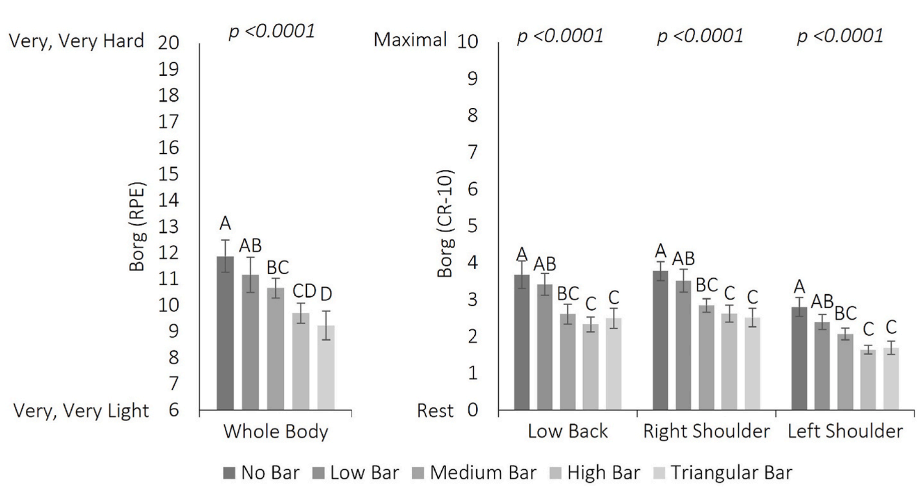

Fig. 7. Mean and standard error (indicated by error bars) of perceived whole-body and localized exertion ratings in the low back and shoulders during crab pot handling in five different banger bar conditions [N = 25]. P-values were calculated from mixed models with the banger bar condition (fixed effect) and the participant (random effect). Different superscript letters (A, B, C, and D) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests (*p < 0.05*).

bar and decreased as the bar height increased. Furthermore, the total sway areas were substantially lower with the bars and showed an inverse relationship with the bar height ($p < 0.0001$). In addition, there were small differences in the median power frequency measures showing lower median power frequency without the bar as compared to the triangular bar ($p < 0.03$).

4. Discussion

This laboratory study aimed to characterize physical risk factors (biomechanical load) associated with musculoskeletal injuries and postural instability during a Dungeness crab harvesting task. This study also evaluated the efficacy of a fishermen-developed control (banger bar) in mitigating the aforementioned risk factors. The results showed

Table 1
Median [25th, 75th percentile] of postural sway measures during crab pot handling in five different banger bar conditions [N = 25]. ML and AP indicate medial-lateral and anterior-posterior directions, respectively.

Parameter	Direction	Banger Bar Condition					P-Value*
		No Bar	Low Bar	Medium Bar	High Bar	Triangular Bar	
Median Power Frequency (Hz)	ML	0.08^{A} [0.07, 0.10]	0.09^{AB} [0.07, 0.12]	0.09^{AB} [0.08, 0.10]	0.09^{AB} [0.08,0.11]	0.10^{B} [0.08,0.11]	**0.02**
	AP	0.08^{A} [0.07, 0.10]	0.10^{AB} [0.07,0.12]	0.09^{AB} [0.08, 0.10]	0.09^{AB} [0.08,0.11]	0.09^{B} [0.08,0.11]	**0.02**
Mean Velocity (mm/s)	ML	93.9^{A} [79.6, 114.3]	86.5^{AB} [61.9, 111.4]	71.7^{BC} [60.0, 97.8]	70.2^{C} [55.0,81.9]	69.1^{C} [56.2,91.2]	**<0.0001**
	AP	95.2^{A} [81.1, 121.9]	87.8^{AB} [62.9, 115.7]	72.2^{BC} [60.1, 100.3]	70.4^{BC} [56.6, 83.5]	69.8^{C} [57.0, 91.7]	**<0.0001**
RMS Displacement (mm)	ML	31.02^{A} [22.8, 36.4]	23.1^{B} [18.9, 30.3]	21.8^{B} [17.5, 25.4]	21.6^{B} [17.3, 27.3]	21.2^{B} [17.7, 26.6]	**<0.0001**
	AP	31.1^{A} [22.9, 36.5]	23.3^{B} [19.0, 30.6]	21.8^{B} [17.7, 25.5]	21.6^{B} [17.3, 27.3]	21.17^{B} [17.7, 26.6]	**<0.0001**
Sway Area (mm^2)		11269.7^{A} [6663.6, 15746.4]	6649.7^{B} [4812.9, 10970.0]	5682.6^{BC} [4158.7, 8938.0]	5126.1^{BC} [3534.1, 9138.9]	5331.4^{C} [3510.4, 7465.7]	**<0.0001**

* P-values were calculated from mixed models with banger bar Condition (fixed effect) and the participant (random effect). Different superscript letters (A, B, and C) indicate statistically significant differences across target sizes based on Tukey HSD post-hoc tests ($p < 0.05$).

that use of the banger bars reduced both the biomechanical load and perceived exertion in the low back, shoulders, and upper extremities during crab pot handling tasks. These biomechanical load and perceived exertion levels further decreased as the banger bar height increased. Moreover, the postural stability measures were significantly improved with the banger bars, especially when the bar height increased.

4.1. Biomechanical load in the low back, shoulders, and upper extremities

Crab pot handling tasks without the banger bars resulted in substantial trunk lateral bending (up to ~43°), exceeding the recommended limits (below 20°) for trunk lateral bending and significantly increasing the risk of low back injuries (Keyserling et al., 1992; Punnett et al., 1991). Moreover, the L5/S1 moment data suggest that the crab pot handling activity may pose substantial stress in the low back. Although the L5/S1 flexion (up to ~120 Nm) and lateral bending moment (up to ~164 Nm) were lower than 200 Nm, the moment threshold corresponding to the NIOSH action limit for compression force and maximum vertebral strength for males aged 20–50 years (Adams, 2004; Gallagher et al., 2002, 2009), the observed L5/S1 moments were comparable to those measured during tasks associated with an increased risk of low back injuries, such as lifting of a 20 kg box (Kingma et al., 2006) and patient handling (Hwang et al., 2020). Further, the L5/S1moments measured may have been underestimated because the crab pot was empty (pot mass: 40 kg) whereas it can weigh as much as 100 kg in the field with baits, gear, and harvested crab (Kim et al., 2022). Therefore, the L5/S1 moments during actual Dungeness crab harvesting are expected to be much higher than those measured in a controlled laboratory setting with an empty crab pot.

Crab pot handling without the bars was also associated with significant shoulder flexion angles (up to ~82°). This laboratory study results were similar to a previous field study that measured the shoulder flexion (up to ~72°) during actual offshore commercial Dungeness crab fishing (Kim et al., 2022). Previous studies have shown that arm elevation greater than 60° is associated with higher risk of musculoskeletal disorders (Silverstein et al., 2008; Bernard et al., 1997). The high shoulder flexion was in line with substantial muscle activities in the trapezius (up to ~54 %MVC) and anterior deltoid muscles (up to ~33 %MVC). Handling without the bars was also associated with moderate muscle activities in biceps (up to ~11 %MVC) and triceps (up to ~35 %MVC). These significant biomechanical load measures in the shoulder and upper extremity regions corroborate the high prevalence of shoulder and upper extremity injuries in the crab fishery (Bovbjerg et al., 2019; Case et al., 2015; FLIPP Survey Results, 2017; Kincl et al., 2019). The shoulder flexion moments observed in this study (up to ~23 Nm) did not exceed the males' shoulder strength capability (~36–61 Nm) (Chow and Dickerson, 2016), which is a threshold for determining increased risks for shoulder injuries (Hoozemans et al., 1998). However, considering the observed extreme shoulder angles and the actual crab pot mass (with baits, gear, and harvested crabs), the realistic shoulder moments can be much greater. These shoulder biomechanical measures consistently indicate that crab pot handling may pose significant risks for shoulder pain and injuries.

The results showed that the low back muscle activity was substantially higher (up to ~95 %RVC) in the right side than the left side. The asymmetric biomechanical load in the low back may be due to the nature of the crab pot handling task. As explained in the methods and Fig. 1, the participants always tilted and banged the pot against the bars to their left. This asymmetric movement can cause asymmetrical muscle activation of the erector spinae muscles (van Dieën, 1996). Moreover, previous studies have shown that asymmetrical movements combined with back flexion and lateral bending can increase compression and shear lumbar spine forces (Marras and Granata, 1997). Hence, these trunk angle and L5/S1 moment data suggest that crab pot handling task may increase the risk of musculoskeletal problems in the low back.

Similar to the biomechanical load measures in the low back, the right trapezius muscle activity was substantially higher (up to ~16 %MVC) than the left side, which can be explained by the asymmetrical nature of the crab pot handling task. Given these differences of biomechanical load in the low back and shoulder regions between right and left, it is recommended that deckhands switch sides periodically during crab pot handling, if feasible, to avoid unbalanced muscle overuse and reduce the risk of musculoskeletal problems.

4.2. Effects of the banger bars on biomechanical load

The results showed that the banger bars significantly reduced the trunk flexion (~27–43%) and lateral bending angles (~31–60%), as well as the L5/S1 flexion (~5–25%) and lateral bending moments (~25–64%). The concurrent reductions in the trunk angles and moments agree with previous findings where decreased low back angles during manual lifting reduced the moment arm between the torso center of mass and L5/S1 (low back joint center), resulting in lower moments and muscle activity (Gallagher et al., 2002; Granata et al., 1997; Jorgensen et al., 2003). The reductions in the trunk angles and L5/S1 moments with the banger bars were supported by the reductions in low back median and peak muscle activity and perceived exertion.

Further, trunk angles, L5/S1 moments, and low back muscle activity decreased as the banger bar height increased. The high and triangular banger bars especially reduced the trunk lateral bending angles below the recommended limit of 20° (Keyserling et al., 1992; Punnett et al., 1991). These results indicate that the higher bars may promote more upright back postures (less flexion and lateral bending) during the crab pot handling task and therefore reduce the risks of low back pain and injuries. This finding mirrored the perceived exertion measures, which also decreased as the banger bar height increased. Specifically, the high and triangular banger bars reduced the perceived exertion in the low back by up to 1 point in the 10-point scale (Borg CR-10) relative to the no-bar condition. This difference exceeded the 9% difference in the visual analog scale, corresponding to a minimum clinically important difference (Kelly, 1998; Ries, 2005).

The banger bars also significantly lowered the biomechanical load in the shoulders (up to ~47%). While the peak right shoulder flexion without the banger bars exceeded the recommended limit of 60°, the high and triangular bars reduced it to around or below 60°. This substantial reduction in the shoulder flexion angles was consistent with the reduced shoulder muscle activities and perceived exertion. Many previous studies that have shown the positive relationships between shoulder flexion and muscle activity (Brookham et al., 2010; Gonçalves et al., 2017). Despite the significant reductions in the shoulder flexion angles with the bars, their effects on shoulder flexion moments were less prominent. This may be attributed to the elbow and forearm postures during shoulder flexion and potential effects of elbow extensions on increasing the moment arm distances to the shoulder joints (Murray et al., 1995). Overall, given the lower shoulder angles, moments, muscle activities, and perceived exertion ratings, banger bars designed with appropriate heights can help reduce the risk of shoulder pain and injuries (Antony and Keir, 2010; Gonçalves et al., 2017).

4.3. Effects of the banger bars on postural stability

The banger bars significantly reduced the COP-based postural sway measures including the mean velocity, RMS displacement, and sway area. As the height of the banger bar increased, these postural sway measures substantially decreased (~7–30%). Such decreases indicate an overall lower deterioration of postural control when a banger bar is used (Corbeil et al., 2003; Horak et al., 2009; Norris et al., 2005; Prieto et al., 1996). In addition, the use of the triangular bar increased the median power frequency measures compared to the no-bar condition (~10–20%), suggesting faster postural adjustments and higher postural stability with a banger bar (Pachori et al., 2008; Paillard and Noé, 2015). However, the interpretation of median power frequency should be done with caution due to its low reliability when compared to other COP-based postural stability measures (Lafond, 2006) and small magnitude differences between the banger bar conditions (~0.01–0.02 Hz). Nevertheless, all the investigated postural stability measures indicate that setting a high banger bar (i.e., high flat bar and triangular bar) may be beneficial in reducing the risks of loss of stability during crab pot handling.

4.4. Effects of banger bar height and design

The results of the biomechanical and postural stability measures indicate that higher bars are associated with lower biomechanical loads and improved postural stability. However, an appropriate height will largely depend on the sorting table characteristics and setup specific to individual fishing vessels. The purpose of the banger bar is to reduce the distance the crab pot would have to travel, and thus the force exerted by the fishermen, to empty the contents of the pot. How much that distance needs to be reduced, which is affected by the banger bar height, will depend on the dimensions of the crab sorting table and may require further research.

Investigating the different designs of banger bars (triangular and flat) showed that the triangular bar was as effective as the high flat bar in reducing biomechanical load (i.e., angle, moment, and muscle activity) and perceived exertion and improving postural balance measures. Such similar effectiveness may have been due to their similar heights. As described in the Introduction, the triangular bar has only one single point of contact that is farther from the hand grips on the crab pot than the flat bar with two contact points. Therefore, the triangular bar can potentially reduce pinch point hazards. Given similar effectiveness and lower pinch point hazard, the triangular banger bar may be recommended when feasible.

4.5. Limitations

The field environment and realistic crab harvesting tasks were recreated based on field-measured vessel configurations and feedback from commercial fishermen. However, the study results are from a simulation of crab pot handling in a controlled laboratory setting and therefore may be different from some field conditions. Notably, the crab pot used in this study was empty; actual crab pots with required bait, gear and crab are generally much heavier. Therefore, the biomechanical load and postural stability measures are likely to be underestimated. Additionally, the study was unable to capture the effects of long-term fatigue on the fishermen since the tasks only involved crab pot handling for a short duration and does not represent when deckhands handle between 50 and 150 pots in a fishing line. Despite these limitations, the involvement of commercial fishermen in the development of the laboratory study and in performing the simulated tasks helped to ensure that the study setup and tasks reflect actual commercial crab harvesting and allow the results to be translated for fishermen and equipment fabricators to improve designs. Regardless, future studies with longer task durations and heavier loads could ensure that simulated tasks in the laboratory better approximate tasks and conditions on vessels.

Another limitation is that the study sample was all male, which may limit the generalizability of the results to females due to gender-related variations in biomechanical properties (Davis and Jorgensen, 2005). However, since the Dungeness crab fleet is predominantly male (as evidenced by our recent survey with over 400 commercial fishermen), our study sample should be representative of the current commercial Dungeness crab fishing population. However, it may be prudent to collect data with female participants in order to address the injury risk of any current and future female fishers.

Lastly, none of the participants were experienced in commercial Dungeness crab fishing activities. As skill level can affect motor unit recruitment strategy (Bernardi et al., 1996), the effects of the banger bar and its height/design on the muscle activity may differ between experienced and inexperienced participants. To minimize such potential effects, all the participants were provided with sufficient practice time to become familiarized with the task, crab pot, and study setup. Moreover, since the task was relatively straightforward (tilting and banging the pot against the bars), it is assumed that the participant's skill level had little effect on the results of our study. Nevertheless, it would be beneficial to conduct further research with experienced workers to gain a more comprehensive understanding.

5. Conclusions

This study demonstrates that a fishermen-developed intervention (banger bar) can be an effective control measure to substantially reduce the biomechanical load in the low back, shoulders, and upper extremities, decrease the perceived whole-body and localized exertion, and improve postural stability for Dungeness crab fishermen. Given the high prevalence of musculoskeletal and fall-related injuries among commercial Dungeness fishermen, the use of the banger bars can have a significant contribution in reducing musculoskeletal, and potentially fall-related, injuries in this population. This study also shows that the higher the banger bar, the lower the biomechanical load, perceived exertion, and postural instability. Moreover, the triangular bar, which had the same height as the high bar, has been shown to be as effective as the high bar in reducing biomechanical load and improving postural stability. Given the similar effectiveness, the triangular bar, which may further reduce pinch point hazards, can be recommended when feasible. However, as this study only evaluated three different heights and the particular bar height can depend on vessel specific parameters, such as the sorting table height, further studies are necessary to determine specific recommended bar heights.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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