Biomechanical Efficacy of an Arm Support and Ergonomic Posture in Reducing WRMSD Risks for Sonographers.

by

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***Abstract*— Work-related musculoskeletal disorders (WRMSDs) are prevalent among sonographers, particularly affecting the shoulder region due to repetitive and static movements. This study introduced an ergonomic posture and a mobile arm support (MAS) to reduce the load of muscles contributing to the stabilization of the shoulder. The experimental setup replicated a conventional cardiac ultrasound examination, using a phantom model and simulations to mimic cardiac ultrasound procedures. Professional cardiac sonographers were instructed to acquire three cardiac views (parasternal long-axis view (PLAX), apical four-chamber view (A4C), and subcostal window(SCW)) while surface EMG and joint angles of the shoulder, elbow, and back were measured. Additionally, subjects were tasked with completing a questionnaire to gather subjective outcomes of usability and satisfaction with the support and ergonomic posture. Muscular activity of the middle deltoid muscular activity (PLAX; F(3,12)10.15,p=.001,η_p^2=.717, A4C; F(3,12)=5.75,p=.011,η_p^2=.590) and superior trapezius (PLAX; F(3,12)=7.05,p=.005,η_p^2=.638) decreased significantly during examinations with postural changes but increased significantly while only support was provided. The support was considered slightly useful (SUS=65.0±6.9, α=.585), but the ergonomic change was considered poor (SUS=43.0.0±14.4, α=.813). The increase in muscular activity was likely caused by incorrect placement of the MAS on the upper extremity and incorrect levels of support. Besides, sonographers reported a MAS would be useful when there is an additional functionality that applies contact force through the MAS. The addition of support to postural changes did not significantly reduce muscular load compared to examinations with only postural changes. Therefore, ergonomic postural change is a sufficient solution for mitigating WRMSDs development due to the only significant decrease in muscular activity.**

Keywords - Ergonomics, Ultrasound Examination, Work-related Musculoskeletal Disorders, Postural Adjustments, Mobile Arm Support.

CONTENTS

I. INTRODUCTION

Musculoskeletal disorders are a prevalent work-related illness and are identified as a prominent cause of absence in the working population [1]–[4]. The term "work-related musculoskeletal disorders" (WRMSDs) refers to a broad range of injuries or dysfunctions affecting the musculoskeletal system including problems with muscles, tendons, ligaments, nerves, bones, and joints affected by activities at the workplace. These disorders are typically a result of poor working conditions and are made worse or persist longer because of those conditions. It serves as an overarching term rather than a specific diagnosis [5], encapsulating a diverse array of conditions such as carpal tunnel syndrome, arthritis, and tendonitis. WRMSDs arise from physical exertion during occupational activities applying stress on the musculoskeletal system. The implications of WRMSDs extend beyond the individual's health, potentially impeding the execution of occupational tasks and thereby decreasing overall productivity [1]. As a result, healthcare practitioners need to relieve themselves of occupational activities to recover from such injuries. Research has underlined the negative effects on productivity resulting from WRMSDs within the healthcare sector, reflecting a significant societal concern [1]–[4].

One area in the healthcare sector that has been of specific interest related to WRMSDs is medical sonography. Sonography or ultrasound, as a diagnostic instrument, is characterized by its user-friendly interface, widespread accessibility, speed, and crucially, non-invasive nature, all of which contribute to its frequent utilization in medical diagnostics [1]. Within the existing literature on WRMSD prevalence in the sonographer population, surveys revealed a prevalence rate ranging from 60% to 97% [3], [4], [6]–[13]. Additionally, Evans et al. [10] discovered that 90.4% of the surveyed sonographers experience pain while performing ultrasound examinations.

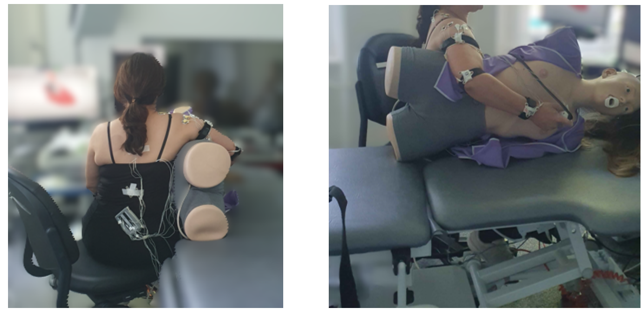
Several contributory factors in the development of WRMSDs were investigated and categorized into three distinct categories [14]. The first category is biomechanical and environmental factors related to workstations, exam room equipment, and -layout. With advancements in this category, standardized exams and protocol management have reduced overall exam time and increased the number of examinations done by each sonographer. Secondly, administrative factors related to scheduling hours of examinations and breaks. This refers to the work done beyond the regulatory scheduled hours, reduced break time, and performing more patient exams due to staffing shortages. Thirdly, worker practices include the postures and actions adopted by sonographers during ultrasound examinations. Analysis of worker practices revealed several factors implicated in WRMSD development, including repetitive motions, forceful and awkward movements, prolonged pressure application, overuse, poor posture, and excessive force and strain [14].

Notably, many of these factors are associated with scanning-related tasks, particularly evident when sonographers engage in repetitive motions throughout a workday. This phenomenon is most prevalent among sonographers conducting high-risk obstetrical ultrasound exams and cardiac sonographers [14]. Ultrasound examination requires the sonographers to adopt a static work posture. Static work postures compromise blood flow to joints, thereby increasing muscular load. To compensate for the muscular load, increased muscle activity is needed to stimulate the force generation within the muscle. However, any period of prolonged muscle activity causes a decline in muscle functionality, leading eventually to muscle fatigue [15]. This fatigue is largely reversible within hours of recovery. If this recovery period is too short, the muscle fatigue can onset structural changes within the muscle, eventually leading to muscle damage [14].

Despite acknowledgment and awareness of the ergonomic challenges among sonographers, research efforts aimed at enhancing ergonomics remain limited aside from the technological advancements of ultrasound systems. Ergonomics, within this context, refers to the design, construction, or adaptation of working conditions to align with the anthropometric, physiological, and psychological needs of the users. The current strategy to mitigate the development of WRMSDs is to ensure sonographers perform ultrasound examinations following guidelines for posture [2], [16]. These guidelines describe the positioning of the patient close to the sonographer to reduce reaching, maintaining arm abduction angles lower than 30^o, changing transducer grips throughout the exams, and optimizing placement of the ultrasound system to avoid neck and trunk twisting [14]. Despite these recommendations, the prevalence of WRMSDs has persisted over time without notable changes [3], [4].

Thesis Objective

The objective of this Master's thesis is to improve the ergonomics of sonographers, with a particular focus on cardiac sonographers, aiming to reduce the development of WRMSDs. According to questionnaires, cardiac sonographers experience more severe complaints and have a higher prevalence of WRMSDs compared to peer employees [8]. Most cardiac sonographers operate the transducer with their right hand [8], which requires a large abduction angle of the right arm, as depicted in Figure 2, since a majority of the exam time they have to reach the cardiac apex [14]. Sonographers allocate approximately 67% of the total examination time to tasks requiring an arm abduction angle exceeding $> 30^o$ and 45% of scanning time to abduction angles exceeding $> 45^o$ [2]. This habit may stem from sonographers prioritizing efficiency in obtaining high-quality images over maintaining optimal ergonomic posture [17]. However, exceeding the recommended abduction angles compromises blood flow to the rotator cuff muscles [14], which increases the development of WRMSDs.



(a) Back view (b) Side view

Fig. 2: Posture adopted by a sonographer in conventional ultrasound examination of the heart, specifically during a parasternal long-axis view. Achieving the correct image requires the sonographer to overreach, requiring large abduction angles, as illustrated in these images.

This pilot research project focuses specifically on addressing the issues within the shoulder region since the shoulder region is the most affected region by WRMSDs among sonographers [3], [4], [6], [10]. As previously mentioned, the abduction angle represents one of the main contributing factors implicated in the development of WRMSDs, alongside overreaching [14]. Studies have revealed that abduction angles significantly affect muscular activity, with a decrease of 64% in the superior m. trapezius muscle activity when the abduction angle decreased from 75^o to 30^o [18]. Furthermore, Wong et al. [19] reported a substantial 54% reduction in muscle stiffness of the m. supraspinatus as the abduction angle decreases from 60^o to 30^o.

Aside from reducing the abduction angle of the upper arm to reduce muscle activity and stiffness, the effects of cushioned arm support were investigated in the same research by Wong et al. [19]. Their study revealed a reduction of 42% in stiffness when the arm was supported at a 30^o arm abduction angle compared to the unsupported arm at the same angle. These changes can be explained through the force coupling of the deltoid muscle and the rotator cuff (Figure 3). The fasciliation of the abduction can be explained through a third-class lever system of the middle deltoid and supraspinatus. To reduce the force needed from these muscles, the load must be lowered. The load is mostly comprised of the weight of the upper extremity and transducer, thus by adding support against this force, the static forces of the middle deltoid and supraspinatus should lower. Another approach for lowering the load is to reduce the abduction angle of the upper arm. Reducing the abduction angle decreases the moment arm between the load and the shoulder joint, subsequently reducing the torque exerted on the shoulder joint. As a result, the force required to stabilize the shoulder joint will lower as well.

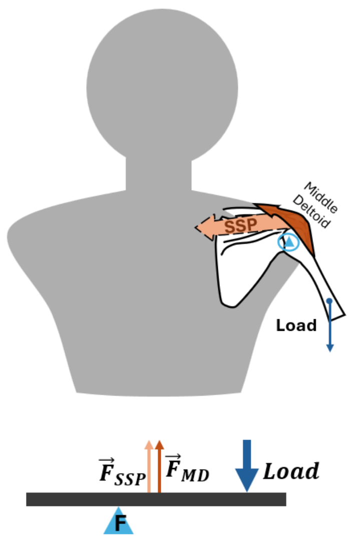


Fig. 3: Illustration of a simplified third-class lever system of the shoulder joint, depicting the middle deltoid and supraspinatus (SSP) during static abduction, inspired by [19]. The fulcrum (F) for this system is located within the shoulder joint. The load in this system is mostly compromised of the weight of the upper extremity and transducer. To maintain stability during abduction, the forces generated by the supraspinatus and the middle deltoid must work in coherence to compensate for the load of the entire upper extremity.

This pilot research project will investigate the biomechanical effects of arm abduction angles and load reduction using surface electromyography (sEMG). While Wong et al. [19] examined the effects of cushion support and abduction angle on muscular load, their experimental setup was used to let subjects apply a constant downward force on a pillow. The current study, however, seeks to explore the influence of support and abduction angles in a more practical setting during a cardiac ultrasound examination. To achieve adequate support while allowing free movement of the upper extremity, a mobile arm support (MAS) will be introduced. The primary advantage of a MAS in a sonographic context is its ability to provide support without constraining movements. This characteristic is particularly significant for sonographers, as it allows them to position the transducer while maintaining the used postures. Additionally, an ergonomic posture will be introduced to cardiac sonographers with its main purpose of minimizing the abduction angle while allowing sonographers to perform examinations right-handly. The position of the patient will be adjusted such that the patient is facing the sonographer while the patient still lies on their left side. To obtain sufficient diagnostic images patients must lie on their left side during cardiac ultrasound examinations.

It is hypothesized that a reduction of the abduction angle and the application of arm support will result in less muscle activity of the deltoid and trapezius muscles during sonographic procedures. It is expected that while both changes will reduce muscular load, the MAS will provide greater muscle relaxation. Although the postural adjustments are expected to reduce the stabilization force required for maintaining shoulder abduction, the introduction of entirely new postures can lead to increased muscle stiffness due to the unfamiliarity with the posture [20]. The adaptations will be tested separately and in combination while professional sonographers perform sonographic-related tasks to determine which yields greater muscle relaxation. It is further hypothesized that combining support with postural changes will result in a greater reduction of muscular load in the shoulder compared to postural changes alone. The introduction of support during postural adjustments can likely mitigate some of the extra stabilization force required for arm abduction due to the awkwardness of the new posture.

II. Methodology

Subjects

Five professional sonographers (age 18-65 yrs; 3 female; 2 male) of the cardiac department at the LUMC have been recruited for this experiment (mean ±SD; height 1.74 ±0.12m; weight 73.6 ±4.62 kg). The exclusion criteria were (1) sonographers still in training, and (2) current injuries in the shoulder region. All participants were right-handed while performing a sonographic examination. This research was approved by the Human Research Ethics Committee (Application Number: 3858) of the Delft University of Technology. All participants signed an informed consent before participating in the pilot experiment.

Materials

The experimental setup was designed to replicate a conventional cardiac ultrasound examination room. It included a stool for the sonographer, an examination bed, an ultrasound monitor, and equipment to simulate cardiac sonography. The simulation equipment consisted of a phantom model, simulation software, and a model transducer (BodyWorks Eve®, Spånga, Sweden). Although this simulation software is generally used for instructional purposes and teaching students to perform correct cardiac sonography, in this pilot experiment, the equipment was utilized to accurately replicate the conditions of a conventional cardiac examination on a patient.

The MAS utilized in this pilot study is the SaeboMAS® (Saebo Inc., Charlotte, USA), dynamic arm support designed to counteract gravitational forces. The SaeboMAS® is commonly used in rehabilitation to support patients with compromised arm functionality, facilitating the recovery of motor skills after a stroke, traumatic brain injury, or other neurological conditions. The design of the SaeboMAS® allows sonographers to apply appropriate contact forces from the transducer on the patient's skin. This contact force is crucial to ensure consistent contact between the transducer and the patient's skin, preventing air gaps and ensuring even distribution of pressure which are essential for reliable diagnostic outcomes.

The position of the transducer and joints was measured with an OptoTrak Certus system (Northern Digital Inc., Waterloo, Ontario, Canada) with a sampling frequency of 100Hz and spatial resolution below 0.1mm. Active optical markers were placed on the right wrist (styloid process of the ulna), the elbow (epicondylus lateralis), the shoulder (acromion), and two on the back (vertebrae cervical 7 (C7) and thoracic 12 (T12)). The markers were fastened using velcro around the respective joint. The cameras were placed behind the participant and on the opposite side of the phantom model within the measurement volume of the OptoTrak cameras.

EMG was recorded with active bipolar surface electrodes (Twente Medical Systems International B.V., Oldenzaal, the Netherlands) on the following muscles: Biceps brachii short head (BC), Triceps brachii long head (TC), anterior Deltoid (AD), middle Deltoid middle (MD), posterior Deltoid (PD), superior Trapezius (ST), and Latissimus Dorsi (LD). The skin surface was shaven and scrubbed clean with an alcohol prep, followed by placement of electrodes according to the SENIAM guidelines [21]. The sampling frequency for sEMG was 1,024Hz.

Experimental Procedure

Prior to the measurements, maximum voluntary isometric contractions (MVCs) were performed and recorded for each measured muscle to normalize muscle activity while participants were standing. A 5-s MVC was done for each muscle using three trials, which included elbow flexion, -extension while the elbow was 90°, shoulder abduction, -adduction, -flexion, and -extension while the upper arm was 45° abducted during abduction and adduction and 60° flexed during flexion and -30° flexed during extension.

The experimental procedure consisted of four conditions: a conventional cardiac sonographic examination, a sonographic examination applying the SaeboMAS®, a sonographic examination performed with improved ergonomic posture (EPI), and lastly a sonographic examination with both the SaeboMAS® and the EPI. The participants were instructed to perform all sonographic procedures right-handedly. The measurement sequence for the four conditions was counterbalanced to minimize potential bias. After the completion of each condition, participants were tasked to complete two short questionnaires: the System Usability Scale (SUS) and the After Scenario Questionnaire (ASQ). The SUS, a fast 10-item 5-point Likert scale survey, was used to assess a user's subjective rating of a product or system's usability in the context of its usage [22]. The ASQ, a 3-item 7-point Likert scale questionnaire, is a reliable tool to quickly measure the user's satisfaction after the completion of each condition [23]. At the end of the experiment, subjects were asked to complete a final questionnaire with open-ended questions. This was done to obtain more detailed information regarding their experiences with the different tested conditions.

Conventional Cardiac Sonographic Examination: During all tested conditions, participants were instructed to obtain three specific cardiac views on the phantom model: a parasternal long-axis view (PLAX), apical four-chamber view (A4C), and subcostal window (SCW), in that order. This sequence was selected to reflect common clinical practice. Participants were tasked to maintain the PLAX and A4C views for three minutes each, and the SCW view for one minute. These predetermined sets of duration were selected to closely represent a standard clinical diagnostic examination and mitigate potential muscle fatigue during the final assessment. The suprasternal notch view examination was not included in this study since it was observed in practice that sonographers spend less than a minute in this view to visualize the aortic arch and its branches. During the conventional cardiac sonographic examination, the phantom model was placed similarly to patient placement in practical examinations (Figure 2). For the SCW, the phantom model was placed on its back for sonographers to place the transducer below the xiphisternum.

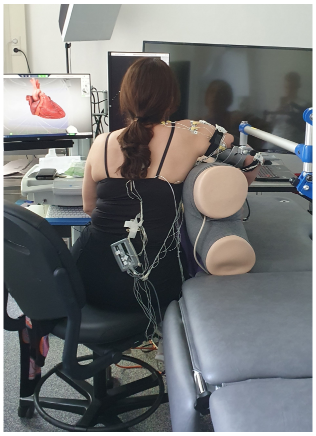
Supported Sonographic Examination: During the supported examination, participants were instructed to place the arm cuff of the SaeboMAS® approximately one-third down the upper arm (Figure 4a). The tension of the SaeboMAS® was set to counteract 80% of the upper extremities weight per subject. This calibrated level of support was chosen to establish a proper balance that facilitates optimal support and provides essential muscle feedback for fine motor skills. The SaeboMAS® was placed on the opposite side of the bed to ensure high visibility of the markers that record joint position. The participants were instructed to obtain the same images and hold them for the same duration as mentioned before.

Ergonomic Posture Improvement: During the EPI condition, participants performed an ultrasound examination on the phantom model while the scanning posture was changed (Figure 4b). The primary object for this posture is to minimize the shoulder's abduction angle while all other cardiac sonography requirements still comply. This meant that the patient was required to lie on their left side during PLAX and A4C acquisition. To comply with the desired goal of reducing shoulder abduction angle and requirement of the patient position, the phantom model will be rotated, with its head at the end of the examination bed while maintaining a lateral position on the left side during PLAX and A4C acquisition. For this measurement, the phantom model was positioned on its back due to the phantom model's instability during the PLAX and A4C examination. In conventional and supported measurements, the phantom is held stable by the sonographer between the upper arm and trunk, as depicted in Figure 2a. However, this is not possible in the EPI condition because subjects have to perform sonography right-handedly. During the SCW examination, the phantom model was positioned likewise on its back and the head at the end of the examination bed.

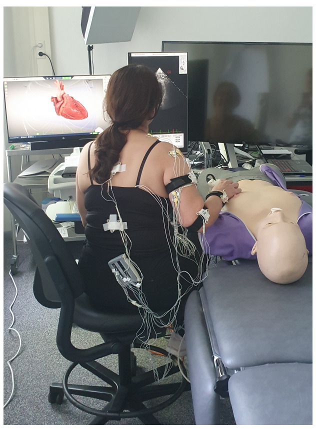
Combination of Support and EPI: This measured condition integrated the elements of both the supported examination and the EPI (Figure 4c). Specifically, the SaeboMAS® was applied to the upper arm while the participant conducted an ultrasound examination within the context of the ergonomic posture.

Data Analysis

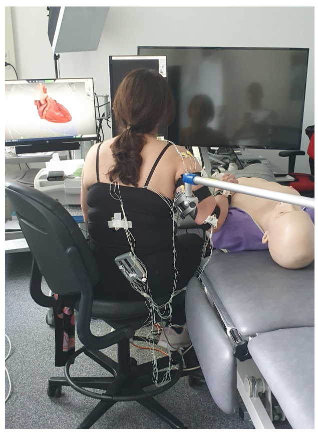
For the analysis of the joint angles and EMG, the data was analyzed using Matlab (Mathworks Inc., Natick, MA, USA). The signals of both electrodes per muscle were first differentiated. Then a 4th order high-pass Butterworth filter was used at 20Hz. The signal was rectified followed by a



(a) Supported Condition



(b) Ergonomic Posture Condition



(c) Supported and Ergonomic Posture Condition

Fig. 4: The conditions tested in PLAX and A4C image acquisition; a) Supported condition in which the SaeboMAS is applied on the upper arm while performing conventional sonography; b) Sonographer performing sonography with ergonomic posture in which the focus lies on lowering the abduction angle of the upper arm while still doing right-handed sonographic examination; c) Sonographer performing sonographic examination with new posture and being supported by the SaeboMAS

2nd order Butterworth filter at 5Hz. Lastly, the average of the whole measurement was calculated for the EMG signals. To normalize the sEMG signals, the MVC value of each muscle with the highest value was calculated from a 1500ms window using the same method.

The position data of all markers were digitally filtered independently in the X, Y, and Z-direction with a 2nd Butterworth low-pass filter at 10Hz. The calculation of the shoulder and elbow angles was based on the definitions described in the kinematic model described by Miyashita et al. [24]. To calculate the shoulder rotational angle, two sets of triangles were established using the markers placed on the shoulder, elbow, and T8 vertebrae, as well as markers on the wrist, elbow, and shoulder. Similarly, for the calculation of the shoulder flexion angle, triangles were formed by the markers on the shoulder, C7, and elbow, and another set using markers on the shoulder, C7, and T8 vertebrae. The shoulder angle was defined by computing the cosine of the inner product of the normal unit vectors projected from the corresponding triangles. Furthermore, the shoulder abduction angle was determined as the angle between the arm line and the trunk in the frontal plane. Elbow flexion was computed by calculating the cosine of the inner product between the vectors defined by the shoulder and elbow markers, and those by the wrist and elbow markers.

Statistical Analysis

Statistical analysis was conducted using IBM SPSS Statistics (SPSS, Inc., an IBM Company, Chicago, IL, USA). A repeated measures Analysis of Variance (ANOVA) was used to determine the statistical difference of the joint angles, the sEMG, and the results of the questionnaires within one measurement and between the conditions. Normality and sphericity were tested using the Shapiro-Wilk- and Mauchly's sphericity tests. Greenhouse-Geisser adjustments were made when the sphericity assumption was not met. A post-hoc analysis using Bonferroni correction was conducted to explore the pairwise comparisons between conditions. Furthermore, the internal reliability of the SUS questionnaire was tested using Cronbach's alpha. Significance for all tests was assumed if $p<0.05$.

III. Results

Participant Characteristics

All participants reported engaging in low- to moderate levels of physical activity 2 to 5 days per week. Participants reported having sonographic-related (lower) back (n=4), upper leg (n=1), hip (n=1), and neck (n=1) complaints.

Joint Angle

No significant difference was found within a measurement of the joint angles of all conditions when comparing the beginning and end of the measurement, indicating that the joint angles were constant during the measurements. The mean joint angles per condition per measurement are summarized in Table I. Mauchly's test indicated a violation of the sphericity in the shoulder abduction angle within the examination of the PLAX ($\chi^2(5)=13.75, p=.024$). A Greenhouse-Geisser correction was applied to adjust for the degrees of freedom. The abduction angle was found to be significantly different in the examination of the PLAX ($F(1.28,5.13)=17.86, p=.007$) and the A4C ($F(3,12)=19.37, p<.001$). Pairwise comparisons indicated a significant difference between the conditions Control and the Supported+EPI (p=.026) in the examination of PLAX. There were no significant differences found in the shoulder abduction angle between the other conditions. In the A4C examination, the shoulder abduction angle was significantly different between the conditions Control and Supported (p=.007), Control and EPI (p=.023), and Supported and EPI (p=.01) conditions.

The shoulder flexion showed significant differences in the A4C ($F(3,12) = 14.16, p<.001$) and SCW examination ($F(3,12) = 5.74, p=.01$). A significant difference was found in shoulder flexion between the Control and the EPI condition (p=.002) and between the Supported and the EPI condition (p=.016) during the A4C examination. Pair-wise comparisons of the SCW examination showed no significant differences.

PLAX Examination				
Joint	Control(Mean±SD)	Supported (Mean±SD)	EPI (Mean±SD)	Supported+EPI (Mean±SD)
EF	65.6°±15.9°	72.6°±20.4°	85.1°±7.8°	73.0°±13.8°
SF	-24.7°±24.0°	-26.5°±17.7°	-20.7°±9.6°	-29.4°±9.4°
SA*	46.9°±13.1°	56.8°±18.3°	18.6°±3.3°	23.1°±5.8°
SR*	0.4°±15.7°	-6.0°±23.2°	-49.4°±18.2°	-40.5°±12.2°
BF	5.6°±2.7°	6.7°±2.7°	11.3°±5.3°	5.3°±6.2°
BLF	4.8°±2.5°	8.2°±7.0°	9.8°±12.1°	-12.3°±14.8°
A4C Examination				
EF	71.3°±11.0°	74.6°±9.9°	107.7°±32.9°	91.0°±32.8°
SF*	-42.7°±12.7°	-44.3°±8.3°	-17.1°±11.3°	-27.1°±11.7°
SA*	33.9°±10.1°	42.6°±9.6°	10.5°±11.0°	18.8°±16.0°
SR*	15.7°±8.0°	23.2°±11.2°	-17.7°±9.4°	-14.4°±8.2°
BF	3.9°±4.8°	6.6°±3.0°	7.9°±5.5°	7.8°±4.7°
BLF	3.9°±7.9°	6.5±7.9°	9.9°±3.9°	10.5°±8.4°
SCW Examination				
EF	74.0°±17.5°	82.4°±31.2°	81.3°±27.6°	89.3°±22.4°
SF	30.8°±17.3°	64.1°±22.6°	29.4°±10.8°	33.5°±21.4°
SA	53.3°±15.2°	45.6°±31.1°	32.2°±17.1°	47.8°±26.0°
SR	-32.1°±8.8°	-30.0°±17.3°	-41.9°±10.7°	-39.5°±14.5°
BF*	8.3°±1.4°	9.7°±1.0°	4.4°±1.3°	5.0°±1.7°
BLF	2.7°±2.8°	1.5°±1.2°	5.6°±4.3°	6.9°±4.3°

TABLE I: Mean(±SD) joint angle in degrees per examination posture and condition (PLAX = Parasternal long-axis view; A4C = Apical four-chamber view; SCW = Subcostal window; EPI = Ergonomic Posture Improvement). * indicates a significant difference with $p<.05$ according to a repeated ANOVA analysis. EF = Elbow Flexion, SF = Shoulder Flexion, SA = Shoulder Abduction, SR = Shoulder Rotation, BF = Back Flexion, BLF = Back Lateral Flexion

Shoulder rotation angle was significantly different in the PLAX ($F(3,12)=12.95, p<.001$) and A4C ($F(3,12)=54.51, p<.001$) examinations. Pairwise comparisons showed a significant difference in shoulder rotation angles between the conditions Control and EPI (p=.004) and Supported and EPI (p=.03) in PLAX examinations. Within the A4C examination, a significant difference was found between the conditions Control and EPI (p=.011), Control and Supported+EPI ($p<.001$), Supported and EPI (p=.018), and Supported and Supported+EPI (p=.004).

sEMG

No significant differences were found between the beginning, middle, and end of the muscle signals during measurements, indicating that no muscle fatigue was present during the measurements. Table II shows a summary of the mean muscle activity per condition per sonographic examination. Significant difference of the MD muscle activation during PLAX($F(3,12)10.15, p=.001, \eta_p^2=.717$) and A4C ($F(3,12)=5.75, p=.011, \eta_p^2=.590$) was found. Pair-wise comparisons revealed no significant differences between any of the conditions in both examinations.

For the ST muscle activation, a significant difference was found during the PLAX examination ($F(3,12)=7.05, p=.005, \eta_p^2=.638$). Pair-wise comparisons revealed a significant difference between the conditions Support and Support+EPI (p=.022). Significant differences were found in the LD muscle activation of PLAX($F(3,12)=3.89, p=.037, \eta_p^2=.493$) and A4C ($F(3,12)=3.62, p=.045, \eta_p^2=.475$) examinations. Pair-wise comparisons showed no significant difference between the conditions.

A significant difference was found in the BC muscle activity during the PLAX examination ($F(3,12)=33.57, p<.001, \eta_p^2=.894$). Pair-wise comparison showed significant differences between the conditions Control and Support+EPI (p=.012), Support and EPI (p=.028), and Support and Support+EPI (p=.026). Mauchly's test showed that the BC violated the assumption of sphericity in the A4C examination ($\chi^2(5)=18.02, p=.005, \epsilon=.352$). After a Greenhouse-Geisser correction, a significant main effect was found in the A4C examination ($F(1.06,4.22)=9.08, p=.036, \eta_p^2=.694$). Pair-wise comparison showed significant differences between the conditions Control and EPI (p=.024), and the Control and Support+EPI (p=.033).

Questionnaires

In Table III, the results of the questionnaires are presented. Cronbach's alpha from the SUS Supported and SUS Supported+EPI was poor(10 items; α = .585, α = .510, resp.), indicating low reliability of this questionnaire, but was good for the EPI condition (10 items; α = .813). Mauchly's test, $\chi^2(2)=1.98$, p=.371 indicated no violation of sphericity for the ASQ questionnaire. A significant difference was found in the ASQ scores between the three tested conditions ($F(2,8)=8.68, p=.010$). Pairwise comparisons showed a significant difference between

PLAX Examination				
Muscle	Control (Mean±SD)	Supported (Mean±SD)	EPI (Mean±SD)	Supported + EPI (Mean±SD)
BC*	12.2% ±3.3%	8.0% ±2.2%	1.5% ±1.2%	1.7% ±1.5%
TC	9.2% ±5.4%	16.2% ±11.8%	5.3% ±4.5%	7.0% ±6.5%
AD	3.1% ±2.5%	2.0% ±1.2%	0.7% ±0.2%	0.6% ±0.4%
MD*	10.4% ±7.7%	15.9% ±7.7%	2.8% ±1.6%	3.5% ±3.0%
PD	10.7% ±10.7%	7.8% ±5.2%	4.9% ±3.6%	6.1% ±5.5%
ST*	24.2% ±22.1%	29.3% ±26.6%	7.6% ±5.6%	10.9% ±14.5%
LD*	33.7% ±11.0%	36.2% ±15.9%	20.0% ±5.9%	23.1% ±8.6%
A4C Examination				
BC*	11.6% ±2.4%	16.5% ±9.1%	3.7% ±2.0%	3.4% ±1.9%
TC	14.4% ±10.3%	9.1% ±6.1%	7.3% ±8.5%	7.3% ±6.6%
AD	2.3% ±0.9%	2.9% ±1.7%	1.1% ±0.6%	1.7% ±1.4%
MD*	18.5% ±11.0%	24.5% ±14.2%	4.8% ±6.0%	5.8% ±5.5%
PD	13.1% ±17.2%	6.2% ±5.8%	6.9% ±7.0%	6.7% ±6.5%
ST	16.8% ±12.8%	18.0% ±11.9%	8.8% ±6.6%	8.7% ±6.7%
LD*	32.7% ±8.0%	32.7% ±10.0%	23.7% ±13.0%	21.8% ±10.0%
SCW Examination				
BC	2.3% ±1.4%	2.1% ±1.3%	2.2% ±1.4%	1.9% ±2.3%
TC	4.9% ±3.0%	6.1% ±3.0%	6.8% ±5.5%	7.4% ±5.7%
AD	1.3% ±0.5%	0.7% ±0.4%	1.4% ±1.2%	0.9% ±0.8%
MD	7.2% ±3.8%	4.0% ±2.0%	6.7% ±2.9%	5.3% ±4.9%
PD	7.7% ±8.3%	7.3% ±5.8%	10.5% ±7.4%	6.7% ±5.8%
ST	8.0% ±5.9%	5.9% ±5.2%	7.7% ±0.6%	6.0% ±4.1%
LD	29.6% ±6.9%	25.8% ±3.9%	29.9% ±11.8%	29.6% ±22.3%

TABLE II: Mean muscle activity in the percentage of isometric MVC per examination posture and condition (Mean±SD). * indicates a significant difference with $p < .05$ according to the repeated ANOVA analysis. PLAX = Parasternal long-axis view; A4C = Apical four-chamber view; SCW = Subcostal window; BC = Biceps, TC = Triceps, AD = Anterior Deltoid, DetlM= Middle Deltoid, PD= Posterior Deltoid, ST = Superior Trapezius, LD = Latissimus Dorsi.

the ASQ of the Supported test and the EPI (p=.037). No significant difference was found between the ASQ scores of the Supported and Supported+EPI (p=1.00) and the EPI and Supported+EPI (p=.20).

From the open-ended questions, four subjects reported that the weightless feeling of the arm during the supported conditions was considered useful. The usefulness of the ergonomic posture lies in the relaxation of keeping the upper arm abducted and the reaching aspect. For the EPI, three participants reported the ergonomic changes were considered useful due to the relaxation in the back and shoulder. However, all participants reported difficulty in obtaining accurate diagnostic images during the PLAX, A4C, and SCW examinations. During the combination of support and ergonomic posture, only one subject responded that the SaeboMAS was considered useful, specifically in the A4C examination. Four subjects suggested adding an extra mechanism to add pressure at the probes end and two suggested changing the arm cuff of the SaeboMAS. One subject mentioned that they felt a numbing feeling in the fingers when performing an ultrasound examination with the SaeboMAS. When asked which of the conditions the subjects would consider using in practice, four responded by using the SaeboMAS while maintaining the old posture.

IV. Discussion

This study aimed to improve ergonomics during ultrasound examinations by providing arm support and ergonomic postural changes. The results indicate that the EPI reduces the muscular activity of the MD and the ST. Thus, the first part of the hypothesis, which considered that reducing the abduction angle would decrease muscular activity, is supported. However, the second part of the hypothesis, which assumed that muscular activity would also decrease with the use of arm support, is rejected. It was observed that the use of the MAS increased muscular activity in the MD and ST, indicating an overall higher muscular load. Finally, the hypothesis stating that combining arm support and EPI would further cause relaxation of the shoulder muscle is partially rejected, as illustrated in Figure 5.

Questionnaire	Supported	EPI	Supported + EPI
SUS	65.0 ±6.9	43.0 ±14.4	52.0 ±9.9
ASQ	4.6 ±0.7	3.3 ±0.5	4.3 ±0.7

TABLE III: Total scores of the questionnaires (Mean ±SD). SUS = System Usability Score, ASQ = After-scenario Questionnaire. SUS scores range from 0 to 100, with 85.5 considered to be excellent. ASQ scores range from 1 to 7, with 4 being average.

Although a slight decrease was observed in muscular activity when comparing the EPI and combined condition, it is not adequate, compared to the changes observed with the EPI alone, to recommend this combined approach for practical use.

Effects of Ergonomic Posture

The EPI demonstrated a reduction in shoulder abduction angles compared to conventional examination, specifically decreasing to 18.6°, 10.5°, and 32.1° during the PLAX, A4C, and SCW examinations, respectively. As a result, the muscular activity of the MD, ST, and even the LD was decreased (Figure 5). These findings align with previous research that investigated the effects of abduction angles on muscular load in the deltoid and superior trapezius [2], [18], [19]. The LD will show similar activity changes due to its antagonistic influence in shoulder abduction and -adduction movements [25]. With this reduction in muscular activity, it can be concluded that the EPI contributes to a reduced overall load on the shoulder joint and surrounding tissue required to support the upper extremity.

Reducing the abduction angle yields several other benefits in mitigating WRMSDs. By decreasing the abduction and flexion angle, the humerus head assumes a more centralized position within the glenoid cavity [26]. This centralization of the humerus head reduces glenohumeral moments, thereby reducing the demand for stabilization from muscles such as the deltoid, trapezius, rotator cuff muscles, and latissimus dorsi [27]. Additionally, lower joint angles promote blood perfusion in these particular muscles [28]. Improved perfusion combined with decreased muscle stress, results in reduced anaerobic energy expenditure during static postures required for sonographic PLAX and A4C examinations, thereby mitigating the accumulation of lactic acid and other metabolites [28], [29]. These metabolites and reduced perfusion are significant contributors to the development of WRMSDs [30]. Since no muscle fatigue was observed in the EPI and the other conditions, the conditions do not impose additional strenuous effects or complications that could lead to the development of WRMSDs.

During the SCW examination, an elevation was noted in the TC and PD. The increased TC activity can be explained by the altered posture, which requires the sonographer to adopt greater elbow extension to ensure adequate transducer contact with the patient's skin. The increase in activity of the PD may be a result of the initial unfamiliarity and discomfort associated with adopting the new posture [31]. However, as sonographers become more familiar with this posture through practice, neural adaption is expected to reduce muscular activation over time [31]. Therefore, with continued use, a decline in muscular activity can be anticipated as sonographers become more proficient and accustomed to ergonomic adjustments.

Sonographers reported that the EPI has poor usability and was less satisfactory compared to the other tested conditions, as indicated by questionnaire responses (Table III). Before the start of the EPI measurements, it was observed that sonographers took notably longer to achieve the correct images. This delay likely contributed to the lower rating of this solution, reflecting their tendency to prioritize efficiency in completing ultrasound examinations [2], [14]. Given that the subjects lacked familiarity with these postural adjustments, training is essential before implementing them in clinical practice. Nonetheless, this pilot research demonstrates promising outcomes using these EPIs in the prevention of WRMSDs when sonographers receive adequate training.

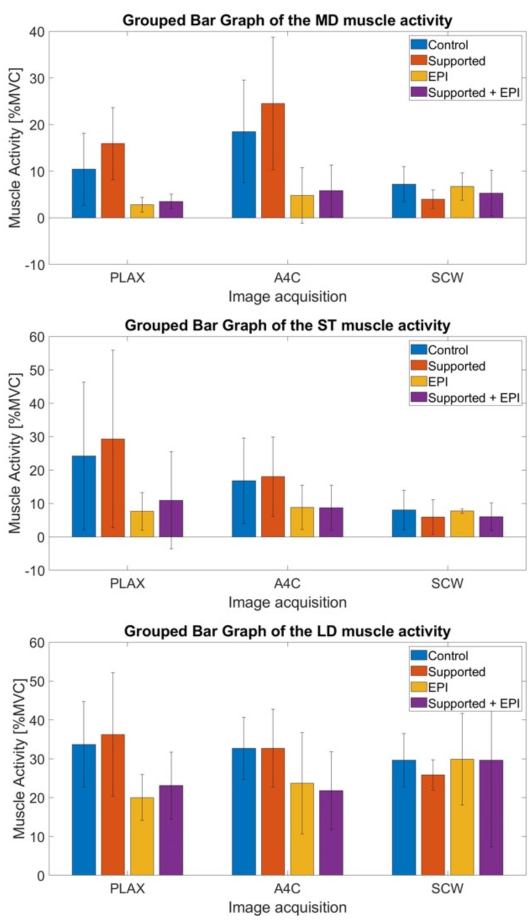


Fig. 5: Visual representation of the mean muscle activity with error bars (in SD) of the middle deltoid (Top), superior trapezius (Middle), and latissimus dorsi (Bottom) in %MVC. Grouped bar plots represent the different ultrasound cardiac examinations under the tested ultrasound examinations.

Effects of Support

Previous research suggested that adding support to the upper extremity would decrease muscular activity in the ST and deltoid [19], [32]–[35], however, the current experiment found opposite results. Specifically, during PLAX and A4C image acquisition, the muscular activity of the MD increased significantly while the subjects had support compared to the control condition. These results suggest that the addition of arm support may have introduced some undesirable mechanisms that result in the observed muscular activity.

One possible explanation for this unexpected outcome is the usage of the SaeboMAS in this study. Typically, the SaeboMAS is placed around the forearm with support levels adjusted to handle 40% to 60% of the upper extremity's weight. This depends on the severity of a patient's neurological complaint.

However, the decision to place the arm cuff on the upper arm was made after a discussion with sonographers before the start of experimentation. These sonographers could express their preference for placement and support levels of the MAS on the upper extremity during ultrasound procedures. As a consequence of these adjustments, the level of support provided may have been excessive for the upper arm, potentially causing a minor superior translation of the humeral head within the glenohumeral joint, which generally increases the inclination angle of the glenoid [36]. Glenoid inclination refers to the amount of tilt of the glenoid relative to the scapula. This increased angle intensifies the superior shear component force of the glenohumeral reaction force, complicating stabilization by the rotator cuff muscles [36]. Cadaver studies have shown that the deltoid muscle must compensate by increasing its contraction force to offset the reduced contribution of the rotator cuff muscles in stabilizing the shoulder during movement involving an abducted upper arm [36]. Additionally, the increased abduction angle in the PLAX (9.9º) and A4C (8.7º) examinations typically lead to reduced concavity compression within the glenohumeral joint [26]. Concavity compression is a stabilizing mechanism facilitated by the rotator cuff muscles, ensuring that the convex of the humeral head is compressed into the concave glenoid fossa, thereby stabilizing the glenohumeral joint against translation forces. Reduced concavity compression requires more stabilization from the rotator cuff muscles and deltoid to maintain joint stability, which becomes more challenging due to superior translation of the humeral head.

Lastly, the increased inclination angle and superior translation mentioned lead to a reduction in the subacromial space. This causes the subacromial bursa to press against the rotator cuff muscle tendons between the shoulder bones. Because of the compression of the tendons, the rotator cuff muscles are weakened to maintain stability during static abduction. As a result, compensation is required from the MD and LD to still achieve this stabilization. A study examining rotator cuff muscle activity during isometric exercises in patients with subacromial impingement syndrome found significantly lower EMG activity in rotator cuff muscles compared to healthy individuals [37]. Moreover, the study indicated increased activity in the MD and ST among patients, further supporting the theory of shifting stabilization requirements between different muscles. To verify these findings, a retest of the experiment was conducted on the researcher. Figure 6 in the appendix demonstrates the MD muscle activity during a simplified PLAX examination. The results exhibit a similar pattern to those observed in this experiment.

A slight decrease in muscular activity was observed in the MD, ST, and LD in the combined condition compared to the EPI condition. However, this reduction was minimal, meaning the combined state would be impractical for clinical use. Additionally, with increased practice of EPI usage, sonographers could potentially lower muscular activity to a level where the MAS would be redundant. The combined condition was considered more useful and satisfactory than only the EPI, but this could be caused by the awkwardness experienced by the new postural changes, see Table III. Furthermore, an increase in the shoulder flexion and abduction between the EPI and combined condition suggests that the support levels might also be too high for this combined condition Table I. This indicated that the support provided by the MAS must be evaluated carefully in its current configuration for this application, underscoring the need for adjustments to achieve an optimal level of support.

During SCW examinations while being supported, a notable reduction in muscle activation of the MD and ST was observed with the MAS. This effectiveness can be responsible for the greater degree of overreach required during this specific examination compared to the other examinations. Therefore, the MAS proves advantageous for sonographers in this context. Similarly, the combination of EPI and support shows potential benefits. However, it is important to note that SCW examinations compromise only a small portion of the overall examination time and may not offer long-term benefits in preventing WRMSDs, as it is not the most physically demanding task for sonographers.

Future research

For future research, it is recommended to replicate this experiment with a larger sample size to validate the findings of this study. Although statistical analyses were conducted to support the observations, some pair-wise comparisons were not detected as statistically significant, likely due to the limited sample size. Furthermore, the main effects of EPI and Support could not be fully explored because the assumption of sphericity could not be tested, again due to the small size. As a result, the main effects were analyzed separately for each muscle, loading to a series of smaller repeated measures ANOVA tests. This increases the potential for false positive statistical results. Therefore, the statistical outcomes should be interpreted with caution in this study.

It is worth mentioning that the measurements of muscular activity in the deltoid, BC, and TC should be considered carefully. This is due to the placement of electrodes and the postures adopted by the sonographers during the experiment. Initially, electrodes were placed while subjects were in a stationary standing relaxed position, with their arm resting naturally alongside their bodies. This neutral position was chosen because of the difference in postures due to the EPI compared to the posture during the conventional ultrasound examination. As subjects performed the examinations, muscle tissue beneath the electrodes may have shifted due to the postures adopted due to the stretching and movements. Consequently, the efficacy of electrodes could have been reduced as the muscles moved relatively away underneath the skin where the electrodes were initially placed. This could have altered the changes observed in this experiment.

Based on the results obtained from the SUS and ASQ questionnaires, all conditions received poor scores for usability and satisfaction. Participants highlighted in the open-ended questions that the arm cuff was uncomfortable and in need of modification. These observations align with reports from one participant who experienced numbness in their fingers during measurements with the MAS, a phenomenon also experienced during the experiment's retest. These findings suggest that the current arm cuff design may be too tight for this specific application. It has been recommended to reposition the arm cuff, but for future studies utilizing the SaeboMAS in the upper arm, adopting arm cuffs with more comfortable material, such as memory foam or air cushioning, is advisable. Such adjustment would conform better to the user's upper arm contours while still ensuring evenly distributing the pressure of the support.

One notable suggestion put forward by participants is the addition of a mechanism at the transducer's end to apply contact force. This recommendation implies a preference among sonographers for added contact forces that would mitigate the need for exerting high contact forces on the patient's skin. For such an addition, variability of the contact force is crucial. The contact force needed to achieve sufficient diagnostic images is dependent on the thickness of subcutaneous tissue [38]. A handheld device with the transducer attached to it should be developed to ensure good precision as in manual manipulation of the transducer. This handheld device could be a standalone device such that it can be combined with the EPI. Otherwise, it is highly recommended to attach such a device to a MAS for conventional ultrasound examinations.

Conclusion

In summary, this pilot study demonstrated that postural adjustments for cardiac sonographers reduce the risk of developing WRMSDs in the shoulder region. The findings indicate that reducing the abduction angle leads to a decrease in muscular activity in the superior trapezius and middle deltoid muscles. This supports the hypothesis that ergonomic postures can alleviate muscular strain during ultrasound examinations. However, the use of a MAS in this study unexpectedly resulted in increased muscular activity in the superior trapezius and middle deltoid muscles, thereby raising the risk of WRMSDs. This suggests that the current support levels and placement of the MAS are not suitable for reducing the muscular load in sonographers. Notably, the placement and support levels of the MAS might have contributed to the observed increase due to superior translation of the humeral head within the glenohumeral joint. Future research is essential to reassess the use of arm support, focusing on optimizing placement and support levels to maximize ergonomic benefits. Additionally, feedback from sonographers suggests the development of a device that variably adjusts the contact force between the transducer and the patient's skin might reduce the physical strain during examinations. To conclude, this study provides valuable insights into mitigating the ergonomic challenges faced by sonographers.

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V. Appendix

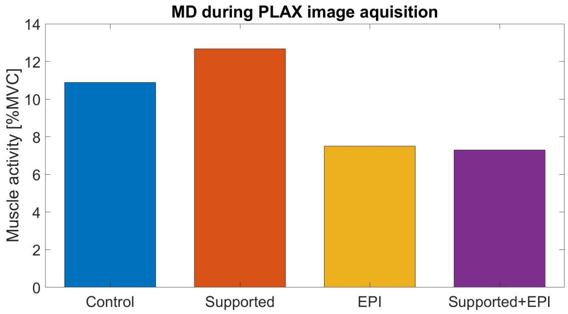

Fig. 6: Amplitude of the EMG signals (in %MVC) of the middle deltoid (MD) during PLAX image acquisition. The test was performed on the researcher self to reevaluate the observed effects of this study. It can be seen that the Supported Condition increases MD activity compared to the control condition while EPI resulted in lowering the MD activity.