

AUTOMATIC POSTURE CORRECTION UTILIZING ELECTRICAL MUSCLE STIMULATION

by

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## **ABSTRACT**

Habitually poor posture can lead to repetitive strain injuries that lower an individual's quality of life and productivity. Slouching over computer screens and smart phones, asymmetric weight distribution due to uneven leg loading, and improper loading posture are some of the common examples that lead to postural problems and health ramifications. To help cultivate good postural habits, researchers have proposed slouching, balance, and improper loading posture detection systems that alert users through traditional visual, auditory or vibro-tactile feedbacks when posture requires attention. However, such notifications are disruptive and can be easily ignored. We address these issues with a new physiological feedback system that uses sensors to detect these poor postures, and electrical muscle stimulation to automatically correct the poor posture. We compare our automatic approach against other alternative feedback systems and through different unique contexts. We find that our approach outperformed alternative traditional feedback systems by being faster and more accurate while delivering an equally comfortable user experience.

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## TABLE OF CONTENTS

LIST OF FIGURES . . . . .	xiv
LIST OF TABLES . . . . .	xxv
CHAPTER 1: INTRODUCTION . . . . .	1
1.1 Poor Posture . . . . .	1
1.2 Slouching . . . . .	4
1.3 Asymmetric Weight Distribution (AWD) . . . . .	5
1.4 Improper Loading Posture (ILP) . . . . .	7
1.5 Electrical Muscle Stimulation (EMS) . . . . .	9
1.6 Research Questions . . . . .	10
1.7 Objectives . . . . .	10
1.8 Contributions . . . . .	11
1.9 Thesis Statement . . . . .	11
1.10 Reader's Guide . . . . .	12
CHAPTER 2: LITERATURE REVIEW . . . . .	13

2.1	Slouching . . . . .	13
2.1.1	Slouching Detection . . . . .	13
2.1.2	Slouching Monitoring without Feedback . . . . .	14
2.1.3	Slouching Detection with Real-Time Feedback . . . . .	16
2.1.3.1	Slouching Preventive Healthcare/Alert Mechanisms . . . . .	20
2.2	Asymmetric Weight Distribution . . . . .	21
2.2.1	Balance and Stability Monitoring . . . . .	22
2.2.2	Asymmetric Weight Distribution with Feedback . . . . .	25
2.3	Improper Loading Posture . . . . .	28
2.3.1	Improper Loading Monitoring and Detection Without Feedback . . . . .	28
2.3.2	Improper Loading Posture Detection with Feedback . . . . .	32
2.4	Electrical Muscle Stimulation (EMS) . . . . .	35
2.4.1	EMS in Rehabilitation . . . . .	36
2.4.2	EMS in Human Computer Interaction . . . . .	37
2.4.2.1	EMS in Activity Training . . . . .	37
2.4.2.2	EMS in Input/Output Interfaces . . . . .	38
2.4.2.3	EMS in Feedback based Immersive Technology . . . . .	40

CHAPTER 3: AUTOMATIC DETECTION AND CORRECTION OF SLOUCHING . . .	43
3.1 Correction Feedback . . . . .	46
3.2 Operation . . . . .	47
3.3 Methods . . . . .	48
3.3.1 Subjects and Apparatus . . . . .	48
3.3.2 EMS hardware operation . . . . .	49
3.3.3 Calibration Process . . . . .	50
3.3.4 Experimental Design . . . . .	52
3.3.5 Research Hypotheses . . . . .	53
3.3.6 COVID-19 Considerations . . . . .	54
3.3.7 Experimental Procedures . . . . .	55
3.3.7.1 Visual feedback and self-correction . . . . .	56
3.3.7.2 Audio feedback and self-correction . . . . .	59
3.3.7.3 EMS feedback and auto-correction . . . . .	59
3.4 Results . . . . .	60
3.5 Discussion . . . . .	65

CHAPTER 4: AUTOMATIC DETECTION AND CORRECTION OF ASYMMETRIC

WEIGHT DISTRIBUTION (AWD) . . . . .	68
4.1 Time and Balance Thresholds . . . . .	69
4.2 Correction Feedback . . . . .	72
4.3 Operation . . . . .	73
4.4 Methods . . . . .	74
4.4.1 Subjects and Apparatus . . . . .	75
4.4.2 Experimental Design . . . . .	77
4.4.3 Research Hypotheses . . . . .	78
4.4.4 COVID-19 Considerations . . . . .	79
4.4.5 Experimental Procedures . . . . .	79
4.4.5.1 Audio feedback and self-correction: . . . . .	81
4.4.5.2 Vibro-tactile feedback and self-correction: . . . . .	82
4.4.5.3 EMS feedback and Auto-correction: . . . . .	83
4.5 Results . . . . .	83
4.5.1 Average Correction Response Times . . . . .	84
4.5.2 User Perception of Correction Feedback Accuracy . . . . .	85
4.5.3 User Perception of Comfort . . . . .	87



4.5.4	User Perception of Task Disruption . . . . .	88
4.5.5	User Perception and Preference . . . . .	90
4.6	Discussion . . . . .	91
CHAPTER 5: AUTOMATIC DETECTION AND CORRECTION OF IMPROPER LOAD- ING POSTURE (ILP) . . . . .		97
5.1	Torso Inclination and Knee Bend Angle Thresholds . . . . .	103
5.2	Correction Feedback . . . . .	106
5.2.1	Correction Strategies . . . . .	107
5.2.1.1	Torso Inclination Correction . . . . .	107
5.2.1.2	Knee Bend Correction . . . . .	108
5.3	Operation . . . . .	109
5.4	Methods: Study 1 . . . . .	111
5.4.1	Subjects and Apparatus . . . . .	111
5.4.2	Experimental Design . . . . .	113
5.4.2.1	Task . . . . .	114
5.4.3	Research Hypothesis . . . . .	116
5.4.4	COVID-19 Considerations . . . . .	116

5.4.5	Experimental procedures . . . . .	117
5.4.5.1	Preparation and Calibration . . . . .	117
5.4.5.2	Experiment . . . . .	119
5.5	Methods: Study 2 . . . . .	123
5.5.1	Subjects and Apparatus . . . . .	123
5.5.2	Experimental Design . . . . .	124
5.5.2.1	Task . . . . .	125
5.5.3	Research Hypothesis . . . . .	126
5.5.4	COVID-19 Considerations . . . . .	126
5.5.5	Experimental procedures . . . . .	127
5.5.5.1	Preparation and Calibration . . . . .	127
5.5.5.2	Experiment . . . . .	127
5.6	Results . . . . .	130
5.6.1	Study 1 . . . . .	130
5.6.1.1	Average Correction Response Times . . . . .	130
5.6.1.2	User Perception of Correction Feedback Accuracy . . . . .	132
5.6.1.3	User Perception of Comfort . . . . .	133

5.6.1.4	User Perception of Task Disruption . . . . .	135
5.6.1.5	User Perception and Preferences . . . . .	136
5.6.2	Study 2 . . . . .	138
5.6.2.1	Average Correction Response Times . . . . .	139
5.6.2.2	User Perception of Correction Feedback Accuracy . . . . .	140
5.6.2.3	User Perception of Comfort . . . . .	142
5.6.2.4	User Perception of Task Disruption . . . . .	143
5.6.2.5	User Perception and Preferences . . . . .	145
5.7	Discussion . . . . .	146
CHAPTER 6: DISCUSSION . . . . .		153
6.1	EMS Intensity . . . . .	153
6.2	Correction Response Times . . . . .	155
6.3	Accuracy of Correction Feedback . . . . .	156
6.4	Comfort and Task Disruption . . . . .	158
6.5	Frequency of Correction . . . . .	159
6.6	Feasibility . . . . .	162
CHAPTER 7: LIMITATIONS AND FUTURE WORK . . . . .		164

7.1	Limitations . . . . .	164
7.1.1	Sensor and Electrode Placement . . . . .	164
7.1.2	Calibration . . . . .	164
7.1.3	Muscle Fatigue . . . . .	165
7.1.4	Mobility . . . . .	165
7.1.5	Gender Imbalance in the Study Population . . . . .	166
7.2	Future Work . . . . .	167
7.2.1	Further investigation . . . . .	167
7.2.2	Voice activated EMS . . . . .	168
7.2.3	Human Tele-Operation . . . . .	169
7.2.4	Automatic Detection and Correction of Wrist Extension . . . . .	170
7.2.5	Automatic Detection and Correction of Poor Neck Posture . . . . .	172
CHAPTER 8: CONCLUSION . . . . .		174
APPENDIX A: HUMAN SUBJECT STUDY QUESTIONNAIRES-SLOUCHING . . . . .		177
APPENDIX B: HUMAN SUBJECT STUDY QUESTIONNAIRES-AWD . . . . .		185
APPENDIX C: HUMAN SUBJECT STUDY QUESTIONNAIRES-ILP . . . . .		194

APPENDIX D: IRB APPROVAL LETTERS . . . . . 201

LIST OF REFERENCES . . . . . 206

## LIST OF FIGURES

1.1	Poor posture due to RSI. . . . .	3
1.2	Correct Vs Incorrect sitting posture. (Left) Incorrect sitting posture with slouched torso, (Right) Correct sitting posture with torso upright. . . . .	4
1.3	Asymmetric weight distribution vs Symmetric weight distribution. (A) AWD posture, (B) Balanced Posture. . . . .	6
1.4	Improper lifting posture vs Proper lifting posture. (A) Improper lifting posture with high torso inclination and low knee bend, (B) Proper lifting posture with upright torso and ideal knee bend. . . . .	8
1.5	Risk of injury and compressive forces exerted on lower back in different lifting activities [190]. . . . .	9
2.1	Passive medical orthosis braces for posture correction. . . . .	21
3.1	Improper posture can have long term health ramifications. Presented here are images of slouched and corrected posture using Electrical Muscle Stimulation: (A) Mobile Gaming - Slouched posture, (B) Mobile Gaming - Corrected posture, (C) Text Entry - Slouched posture, (D) Text Entry - Corrected posture. . . . .	43
3.2	Physiological Feedback Loop: Automatic Slouching Detection and Correction System. . . . .	44

3.3	Wireless IMU sensor placement for posture monitoring and detecting slouched posture:(A) Side view showing sensor placement on left deltoid, (B) Front view showing sensor placement below center of collar bone above the chest, (C) Side view showing sensor placement on right deltoid. . . . .	45
3.4	EMS electrode placement on rhomboid muscles for auto-correction using EMS feedback. . . . .	46
3.5	Automatic Detection and correction of Slouching: Graph showing EMS activation and deactivation. When torso inclination and shoulder roll angles cross the threshold and remain there for a duration of 5 seconds, EMS is activated. EMS is deactivated when upright posture is restored. . . . .	47
3.6	EMS Hardware Block Diagram. . . . .	50
3.7	A step-by-step description of the calibration process for optimal EMS intensity	51
3.8	Text entry study showing 50-50 split screen with a PDF document (zoom set to 40%) on the left and a Microsoft Word document (zoom set to page width) on the right. Participants were required to read from the PDF document and type in to the Word document. . . . .	57
3.9	Mobile game study showing lobby area of PUBG mobile prior to start of the game. . . . .	57
3.10	Text entry study-visual feedback: showing Windows 10 pop-up visual notification on the bottom right of the screen. (A) To correct posture when slouching is detected. (B) After posture has been corrected. . . . .	58

3.11	Mobile game study-visual feedback: showing visual notification badges drop down from the top of the display. (A) To correct posture when slouching is detected. (B) After posture has been corrected. . . . .	58
3.12	Average Correction Response Times (in Seconds) across (A) Text Entry and (B) Mobile Game for all correction feedback types - (1) Visual, (2) Audio, (3) EMS. Error Bars: 95% CI. . . . .	62
4.1	Impaired balance can have long-term health ramifications. Presented here are images of asymmetric weight distribution (AWD) due to prolonged standing and restored balance conditions using electrical muscle stimulation (EMS): (A) AWD right, (C) AWD left, (B) & (D) EMS feedback based stabilization and restoration of balanced posture. The red arrows indicate direction of progressive AWD and green arrows indicate a counter-weight shift balance stabilization due to EMS feedback correction to the tibialis muscle. . . . .	68
4.2	Physiological feedback loop: Automatic asymmetric weight distribution detection and correction system. Asymmetric weight distribution posture (top) illustrates leaning to either side and the auto-corrected posture (bottom) illustrates the restored balanced posture achieved through a counter-weight shift strategy using EMS. . . . .	70
4.3	Some examples of typical actions performed during standing activities based on movement observations of employees taking breaks after standing. (A) Lean slight left, (B) Lean slight right, (C) Balanced, (D) Calf raise and reset, (E) Lift left leg and reset, (F) Scratch leg and reset, (G) Sway and reset, (H) Lean extreme right, (I) Lift right leg and reset, (J) Lean extreme left. . . . .	71



4.4	Balance ratio patterns of the 10 actions performed by users (illustrated in Figure 4.3) for the tuning process to determine balance and time thresholds for AWD detection. The lean actions representative of AWD exhibited higher balance ratios and for prolonged time durations in comparison to the other actions. . . . .	72
4.5	Automatic Detection and correction of AWD: Graph showing EMS activation and deactivation. When the user’s balance ratio approached and crossed preset balance ratio and time thresholds, EMS was activated for AWD correction. EMS was deactivated when 50:50 balance was restored. . . . .	74
4.6	Participants played PUBG mobile in the mobile game condition. Image shows the lobby area of the game prior to starting. . . . .	76
4.7	Evaluation of the effectiveness of our automatic approach across 2 different application types- Quiet Standing (A), (B), (C) and Mobile Game (D), (E), (F). Quiet Standing: (A) AWD Left, (B) Balanced, (C) AWD Right. Mobile Game: (D) AWD Left, (E) Balanced, (F) AWD Right. . . . .	78
4.8	Haptic motor unit and EMS electrode placement on the tibialis muscle. (a) Vibro-tactile feedback is delivered to the legs through the haptic motor units placed on each leg. (b) EMS feedback is delivered through EMS Electrodes placed on the tibialis muscle on each leg. . . . .	82
4.9	Average correction response times (ACRT) across (a) Modality, & (b) Application type. Error bars:95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game. . . . .	85

4.10	User perception of correction feedback accuracy across (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game. . . . .	86
4.11	User perception of Comfort (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game. . . . .	88
4.12	User perception of Task Disruption (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game. . . . .	89
4.13	User perception mean rankings for correction feedback accuracy, posture awareness, comfort, and task disruption across all modality and application types. Likert Scale: 1-meaning not at all, 7-meaning completely. QS:Quiet Standing, MG:Mobile Gaming. Error bars: 95% CI. . . . .	90
4.14	Average Correction Response times across all modality and application types. Error bars:95% CI. . . . .	92
5.1	Improper loading posture can lead to lower back injuries and pain. Presented here are images of improper loading posture (A) & (B), corrected posture using Electrical Muscle Stimulation (C), and completion of the lifting activity (D-I). . . . .	97

5.2	Physiological Feedback Loop: Automatic Improper Loading Posture Detection and Correction System. Improper loading posture (top) illustrates excessive torso inclination and insufficient knee bending that can lead to long term low back pain and the auto-corrected posture (bottom) illustrates the restored proper lifting posture achieved through using EMS. . . . .	99
5.3	Wireless IMU sensor placement for improper loading posture detection: (A) Front view showing sensor placement below center of collar bone above the chest, (B) Front view showing sensor placement above each knee, (C) Front view showing sensor, box placement and experiment set up. . . . .	100
5.4	Torso inclination and knee bend angular change patterns exhibited by young adults while lifting each of the four boxes. . . . .	101
5.5	Average maximum torso inclination angles exhibited by young adults while lifting different boxes of different weights and sizes. Error bars:95% CI. . . .	102
5.6	Average maximum knee angles exhibited by young adults while lifting different boxes of different weights and sizes. Error bars:95% CI. . . . .	102
5.7	Torso inclination and knee bend angular change patterns exhibited by certified trainers while lifting different boxes of different weights and sizes. . . . .	104
5.8	Average maximum torso inclination angles exhibited by certified trainers while lifting different boxes of different weights and sizes. Error bars:95% CI.	105
5.9	Average maximum knee angles exhibited by trainers while lifting different boxes of different weights and sizes. Error bars:95% CI. . . . .	105

5.10	EMS electrode placement on (a) Rhomboid muscles for torso inclination correction, & (b) Hamstring muscles for Knee bend correction. . . . .	107
5.11	Automatic Detection and Correction of ILP: Graph showing EMS activation and deactivation. When ILP is detected from the user's high torso inclination and low knee bend angle, EMS was activated on the torso/knees for ILP correction. EMS was deactivated when ideal torso inclination and knee bend angles are achieved. . . . .	110
5.12	Experimental setup showing the four different sized boxes with different weights that need to be moved from zone A to B, and vice versa based on instructions presented to them via a Microsoft Surface 50 inch display placed in front of them. . . . .	112
5.13	An example of participant performing the task: (A) Lifting box 3 with ILP from Zone A, (B) Receiving correction feedback to restore proper torso inclination and knee bend lifting angles, (C) Completing the lift, and (D) Moving to Zone B and placing it in Zone B. . . . .	114
5.14	Experimental setup showing instructions presented to participant. (a) Participant view, (b) C# User interface display on Microsoft Surface 50 inch display. Commands to lift and move boxes are displayed in the green display box. . .	119
5.15	Average correction response times (ACRT) across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . .	131

5.16	User perception of correction feedback accuracy across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	133
5.17	User perception of Comfort across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	134
5.18	User perception of Task Disruption across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	136
5.19	User perception mean rankings for correction feedback accuracy (CFA), ILP correction assistance (CA), comfort, and task disruption (TD) across all feedback modalities and correction strategy types. Likert Scale: 1-meaning not at all, 7-meaning completely. T: Torso inclination correction strategy, K: Knee bend correction strategy. Error bars: 95% CI. . . . .	137
5.20	User preference of (a) Feedback Modality, & (b) Correction Strategy. . . . .	138
5.21	Average correction response times (ACRT) across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V:Vi bro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	140
5.22	User perception of correction feedback accuracy across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	141

5.23	User perception of Comfort across ((a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	143
5.24	User perception of Task Disruption across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy. . . . .	144
5.25	User preference of feedback modality in (a) Torso inclination correction strategy & (b) Knee bend correction strategy. . . . .	145
5.26	Average Correction Response Times of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile feedbacks. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI. . . . .	148
5.27	Mean User Ranking for Correction Feedback Accuracy of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI. . . . .	149
5.28	Mean User Ranking for Comfort of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI.	150
5.29	Mean User Ranking for Task Disruption of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI. . . . .	151

6.1	Average correction response times for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities. Error bars: 95% CI. . . . .	156
6.2	User Perception of Correction Feedback Accuracy for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI. . . . .	157
6.3	User Perception of Comfort for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI . . . . .	158
6.4	User Perception of Task Disruption for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI . . . . .	159
6.5	Frequency of Corrections: (A) Slouching, (B) AWD, (C) ILP. Error bars: 95% CI. . . . .	160
6.6	Time between Corrections: (A) Slouching, (B) AWD, (C) ILP. Error bars: 95% CI. . . . .	161
7.1	Voice activated EMS prototype responding to specific voice commands recognized by the speech recognition engine for (A) Activation of EMS on hand, (B) EMS invoking involuntary contraction of hand muscles for grasping object, (C) EMS invoking involuntary contraction of Bicep muscles for lifting object, (D) Deactivation of EMS on bicep for dropping object. . . . .	168

7.2	Human Tele-operation EMS prototype demonstrating the transfer of muscle activity from Operator to Performer. (A) The operators' bicep fitted with EMG sensors records muscle activity during a bicep flex action. (B), (C), and (D) The operators' EMG signal representative of the bicep muscle activation is applied as an electrical stimulus to the bicep muscle performer to generate the same physiological response of the bicep flex action. . . . .	169
7.3	Correct-Me: A flexible 3D printed glove with embedded bend sensors to automatically detect and correct wrist extension. . . . .	171
7.4	Correct-Me: Automatic detection and correction of wrist extension. . . . .	171



## LIST OF TABLES

3.1	User ranking on posture awareness, devices, and EMS. User ranking on a 7-point Likert scale. . . . .	49
3.2	Average Slouching Angles (degrees). . . . .	61
3.3	Friedman test results on the user ranking for H2-H5. . . . .	62
4.1	User ranking on posture awareness, devices, and EMS. User ranking on a 7-point Likert scale. QS: Quiet standing, MG: Mobile game. . . . .	76
4.2	2-Factor ANOVA: Average Correction response times (ACRT). M: Modality, A: Application. . . . .	84
4.3	2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). M: Modality, A: Application. . . . .	86
4.4	2-Factor ANOVA: User perception-Comfort. M: Modality, A: Application. . . . .	87
4.5	2-Factor ANOVA: User Perception-Task disruption (TD). M: Modality, A: Application. . . . .	89
5.1	Size and Weight of Boxes. . . . .	100
5.2	User ranking on lifting tasks, ILP, alert devices, and EMS. User ranking on a 7-point Likert scale. . . . .	113

5.3	User ranking on Lifting task, ILP, alert devices, and EMS. User ranking on a 7-point Likert scale. T:Torso inclination correction strategy, K: Knee bend correction strategy. . . . .	124
5.4	2-Factor ANOVA: Average Correction response times (ACRT). FM: Feedback Modality, CS: Correction Strategy. . . . .	131
5.5	2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). FM: Feedback Modality, CS: Correction Strategy. . . . .	132
5.6	2-Factor ANOVA: User perception-Comfort. FM: Feedback Modality, CS: Correction Strategy. . . . .	134
5.7	2-Factor ANOVA: User Perception-Task disruption (TD). FM: Feedback Modality, CS: Correction Strategy. . . . .	135
5.8	2-Factor ANOVA: Average Correction response times (ACRT). FM: Feedback Modality, CS: Correction Strategy. . . . .	139
5.9	2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). FM: Feedback Modality, CS: Correction Strategy. . . . .	141
5.10	2-Factor ANOVA: User perception-Comfort. FM: Feedback Modality, CS: Correction Strategy. . . . .	142
5.11	2-Factor ANOVA: User Perception-Task disruption (TD). FM: Feedback Modality, CS: Correction Strategy. . . . .	144
6.1	Mean EMS Intensity utilized for stimulating different muscles for correcting poor posture . . . . .	154

# CHAPTER 1: INTRODUCTION

## 1.1 Poor Posture

Posture is the manner in which we support our bodies in different everyday activities like standing, sitting, or lying down. The alignment of the body parts bolstered by the correct muscular tension against gravity plays a crucial role in maintaining good and healthy posture. Posture can be identified as static or dynamic motor habits developed based on morphological and physiological backgrounds of individuals [109]. Posture also serves as an indicator of the body's proprioceptive efficiency for neuro-muscular coordination, and also reflects well-being, activity level, and personality of an individual. Cultivating good postural habits allows correct alignment of the head, neck, torso, and legs for maintaining healthy posture.

Poor posture leading to Repetitive Strain Injuries (RSI) are increasingly becoming prevalent all over the world. Modern living has adversely impacted human motor function and behavior, and has resulted in increasing sedentary lifestyle tendencies [25, 30, 145]. In adaptation to the changing lifestyle and daily behavior, the human body performs subconscious changes to the proprioceptive control systems which may lead to forming new postural habits that may result in poor posture. Advancements in technology with televisions, computers, smartphones, gaming, social media, and motorized transport options have resulted in a decline in regular physical activity which contributes to poor posture in young students [105, 109]. Improper occupational customs, unwarranted workstation arrangements, and increasing multi-tasking requirements are often the biggest factors contributing to the development of poor postural habits in the adult working population.

Poor posture has also been linked to health deterioration, and low productivity at the workplace [9]. Repetitive processes such as use of computer systems, smartphones, prolonged standing/leaning

tasks, and repetitive lifting actions presents a high risk of RSI such as wrist extension, neck cradling, forward neck, slouching, asymmetric weight distribution and chronic lower back pain. These RSI if not detected, analyzed, and corrected at early-stage, lead to the development of poor posture habits which induce soreness, intense pain, trigger point pain, and muscle tightness in the associated regions. If untreated, these conditions may evolve into chronic musculoskeletal injuries such as Carpel-Tunnel syndrome, chronic neck pain, lower back pain, knee & ankle injuries, and gait imbalance [169].

Nearly \$90 billion are spent annually in the USA, for treating repetitive strain injuries (RSI) and lower body injuries arising out of poor workplace postures [39, 43]. Figure 1.1 illustrates the proportions of the population affected by RSI of wrist, neck, shoulder, and lower back. Additionally, orthopedic doctors have claimed that poor postural habits cultivated at the workplace such as prolonged sessions of sitting, standing, leaning and repetitive lifting will have damaging effects in the long run on a person's health conditions [9]. Recently, a study showed that poor posture affects the transverses abdominus muscle. The transverses abdominus muscle is a muscle layer of the anterior and lateral abdominal wall which is layered below the internal oblique muscle responsible for maintaining the torso in an upright position while standing and sitting. The study determined that thickness of the transverses abdominus muscle is significantly less when a person maintained a poor posture [169]. This muscle dysfunction or dystrophy caused by poor posture is directly associated with lower back pain. Lower body injuries are one of the noted root causes of disability in the world and affect approximately 80% of the world population at some point in their lives [96, 113, 175].

Another study compared the stress and performance levels between participants who were asked to maintain good posture versus participants who were asked to maintain poor or irregular posture. The results reported higher stress and lower performance amongst the participants who emulated poor postural habits [174]. Some studies also indicate that even maintaining good posture for a long time might be considered a bad postural habit as the muscles in the spine could stop generating



Figure 1.1: Poor posture due to RSI.

substances necessary for normal biological operations [21]. Although maintaining a good posture is essential, it is important to alternate or change posture over a period for maintaining good health.

Current intervention technology only deals with detecting poor postures, providing alert mechanisms, and relying on the users' willingness to correct their postures themselves. This presents a gap in research for automatically alerting, correcting, and maintaining good posture when poor postural habits have already been formed. As a result, there is a dire need for implementation of an ergonomic intervention technology with the capability of detection and subsequent automatic correction for restoring and maintaining good posture. In this work, we focused on three significant posture problems arising out of prolonged activity or repetitive actions:

1. Slouching
2. Asymmetric weight distribution (AWD)
3. Improper loading posture (ILP)

## 1.2 Slouching

In the past decade, most of the working community have desk jobs that often require long durations of being seated at a computer workstation, and college students who spend numerous hours hunched and leaning towards their laptops while studying. These practices place significant strain on their shoulders, neck, and spine and over time develop into poor postural habits that lead to low performance and severe health issues in the long run. Figure 1.2 shows correct posture and slouched posture while sitting at the workplace. The repetitive strain placed on the shoulders, neck and spine gradually results in the development of poor postural habits. The development of these poor postural habits especially slouching causes the pectoral (chest) muscles to overly contract resulting in unnatural curvature of the spine, rounding of the shoulders, and thoracic regions. Consequently, this unnatural curvature of the spine results in weakening of the rhomboid (shoulder), and trapezius (neck) muscles, and causes intense pain over a period of time.

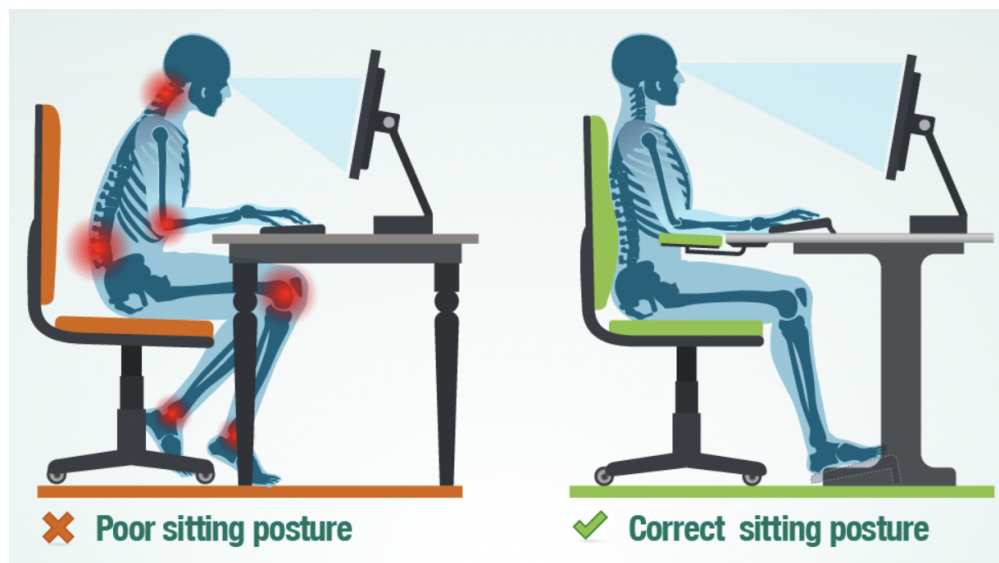


Figure 1.2: Correct Vs Incorrect sitting posture. (Left) Incorrect sitting posture with slouched torso, (Right) Correct sitting posture with torso upright.

The current interventions or solutions for poor slouched posture comprise educating the working population about guidelines for configuring proper workplace environment for maintaining correct posture, guidelines for positioning keyboards, monitor viewing angles, chair height and arm rest adjustments are also recommended [214]. Additionally, injured workers are educated by occupational therapists for development of healthy and correct workplace postural habits. However, workers are often found struggling to maintain these healthy postural habits on their own. The development of new healthy postural habits to replace already developed poor postural habits poses a significant challenge and requires an additional feedback system that alerts the users to maintain correct posture and prevent poor postural habits from re-establishing. Although, Multiple Resource Theory establishes that humans are capable of performing multiple parallel tasks in spite of the increased cognitive demand [201], workers are often found to be highly engaged in a task to automatically identify their poor posture and correct their posture.

As current intervention technology offers only slouching detection and requires users' conscious effort to correct slouched posture, there is dire need for the implementation of a wearable intervention technology with autonomous capabilities for slouched posture detection and correction to prevent this chronic problem with little to no disruption of the primary task and facilitate proper posture maintenance during work and gaming activities.

### **1.3 Asymmetric Weight Distribution (AWD)**

The maintenance of stable posture is important as two-thirds of our body mass, and delicate organs are being supported by our legs which form a narrow base of support. Asymmetric weight distribution (AWD) characterized by postural sway and impaired standing balance has been known to be responsible for multiple health conditions resulting in reduced functional ability [202]. Numerous posture-related health issues such as lower back pain [139], anterior cruciate ligament

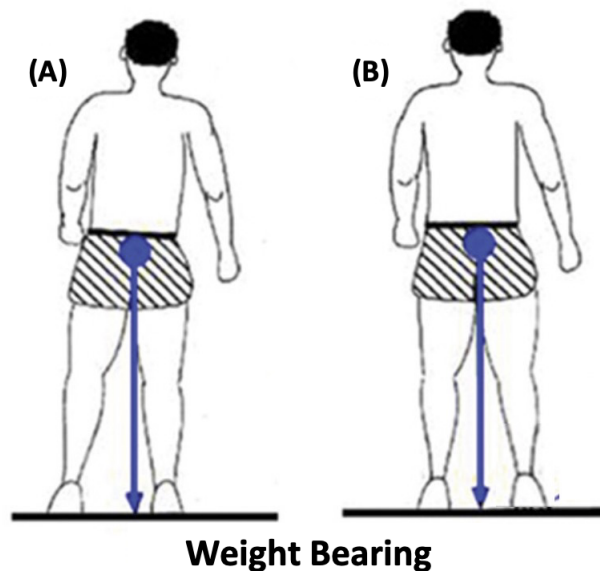


Figure 1.3: Asymmetric weight distribution vs Symmetric weight distribution. (A) AWD posture, (B) Balanced Posture.

ruptures [85, 133, 155], and knee and ankle injuries [62, 111] are associated with an increase in postural sway and AWD. Postural control is a constant re-establishment process of balance and is integral to the safe execution of most movements in our daily life. Posture adjustment relies primarily on the integration of different sensory feedback such as the visual, vestibular, and proprioceptive control systems. Subconscious proprioception, in the form of awareness from muscle receptors, and joints also play an important role in the control of posture and balance. However, the effectiveness of our body's postural control system decreases with cognitive demand, age, and injuries, and imposes a critical demand on the postural control system especially while being engaged in additional cognitive tasks during standing activities. Although conscious proprioception plays a crucial role in gross muscular and full-body posture adjustments, poor postural habits and impaired proprioception may lead to increased postural sway, AWD, and even loss of balance [10]. AWD may lead to increasing instability, subsequent injury, and progressive deterioration of posture and gait [189].



Investigation of AWD has provided valuable information in an array of situations such as fall detection and prediction in the elderly [87], evaluation of balance-related disabilities (Parkinson's disease, stroke, and concussions), and lower body post-surgery rehabilitation [6, 7, 59, 134, 178].

Prolonged standing causes muscle dysfunction, or dystrophy of the muscles of the leg and often leads to unequal load distribution on the hips, knees, ankles, and feet which are responsible for stabilizing the torso in an upright position and is directly associated with lower back pain [169]. As existing intervention technology attempts only postural sway detection and necessitates the participants' attention and effort to self-correct imbalance, there is a need for the development of an automatic wearable intervention technology with the capability for AWD detection and subsequent correction to facilitate proper posture maintenance during tasks involving prolonged standing hours such as work, recreational, and gaming activities.

#### **1.4 Improper Loading Posture (ILP)**

Chronic lower back pain caused by improper loading posture while lifting objects has been known to affect nearly 80% of the population at some point in their lifetime [96, 175]. Preventing back injuries poses a major workplace safety challenge. Lower back pain is increasingly becoming widespread among the working population especially manual workers such as industry laborers, construction workers, delivery men, carpenters, welders, farmers, health assistants, teachers, and office workers prone to RSI and poor postural health [53]. The major risk factors for lower back pain include overloading, and improper loading due to repetitive mechanical stresses on lumbar muscles, ligaments, and vertebrae [108]. Figure 1.4(A) illustrates improper loading posture with high torso inclination and low knee bend which places a stress on the lower regions of the spine. Figure 1.4(B) illustrates proper loading posture with an upright torso and knee bend which allows the legs to support the lift and minimize the stress placed on the lower back.

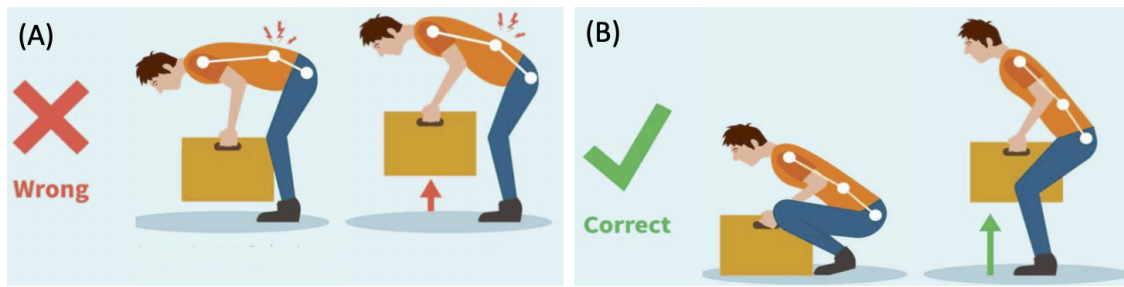


Figure 1.4: Improper lifting posture vs Proper lifting posture. (A) Improper lifting posture with high torso inclination and low knee bend, (B) Proper lifting posture with upright torso and ideal knee bend.

The Occupational Safety and Health (OSH) academy estimated compressive forces exerted on the lower back in different lifting activities and a comparison of the risk of injury for different lifting conditions is illustrated in Figure 1.5 [190]. They utilized the Michigan 2-D static strength model to estimate the compressive forces and illustrate that the bent over lifting posture presents the highest risk of lower back injury. The repetitive mechanical stresses on the lower back can occur in occupational and non-occupational environments during common everyday activities such as leaning and lifting [26, 150, 182]. Other potential risk factors such as bending, twisting, and prolonged static leaning workplace postures have also been known to cause lower back pain [20]. Even lifting moderate loads repetitively can increase the risk of lower back pain [32, 36, 83], weaken or damage the lumbar muscles [5], and could cause intervertebral disc degeneration or herniation [68]. The repetitive stresses exerted on the ligaments and muscle tissues can also result in fatigue, strain and discomfort [46, 179]. This widespread characteristic of lower back pain due to improper loading has led researchers to evaluate different loading strategies, develop improper loading detection techniques, and lift assistive devices to support proper loading posture. As existing intervention technology offers only ILP detection and requires the users' willingness and effort to correct ILP, there is a fundamental need for the development of an autonomous ILP detection and correction system capable of automatically detecting ILP early in the lift phase and subsequently correcting it

to mitigate risk of injury to the lower back.

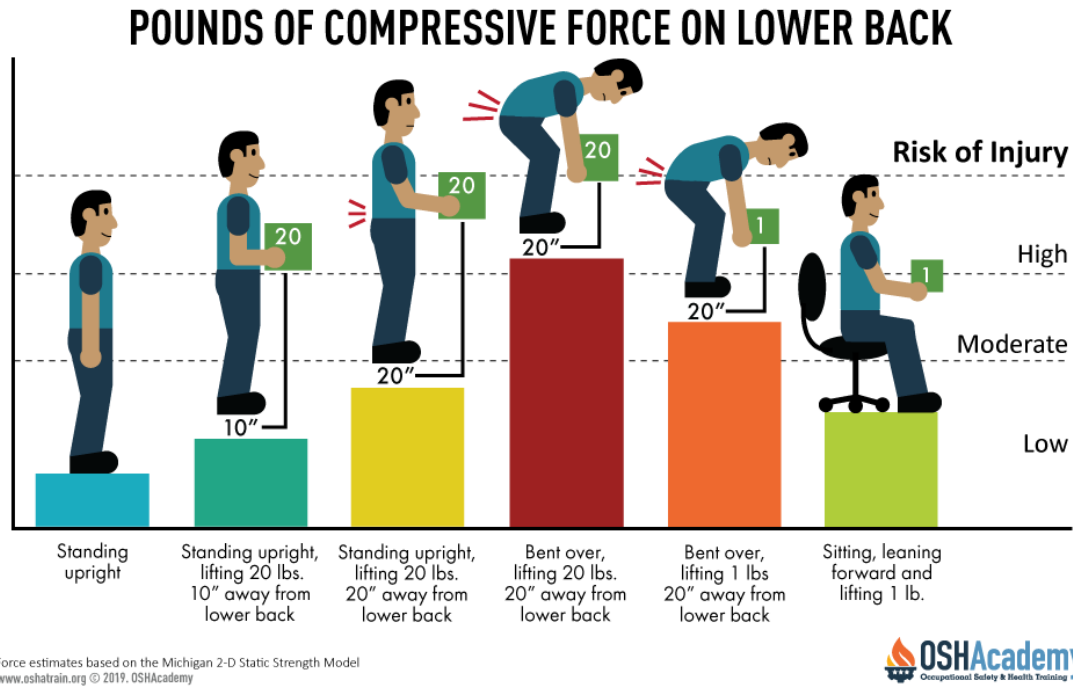


Figure 1.5: Risk of injury and compressive forces exerted on lower back in different lifting activities [190].

## 1.5 Electrical Muscle Stimulation (EMS)

Electrical muscle stimulation has been shown to induce involuntary muscular contractions for generating physiological responses [41, 165, 184]. Integration of EMS with a poor posture detection system can be utilized to correct poor habitual posture and restore/maintain good posture through involuntary muscular contractions when strategically applied in specific patterns and at distinct locations. The design of an autonomous poor posture detection and correction system also presents the challenge of integrating the sensor based poor posture detection system and EMS with wearable intervention technology. This has paved the way for this research in developing sensor based

wearable technologies that employ sensors for detecting the poor postures such as slouching, AWD, and ILP, and subsequently applying electrical muscle stimulation to specific muscles for automatic correction of these poor postures. Our work aims to explore and provide insights into differences between our approach of automatic posture correction and posture self-correction in traditional visual, audio, and vibro-tactile feedback techniques.

### **1.6 Research Questions**

1. Can sensor based systems accurately detect poor posture such as slouching, AWD and ILP?
2. Can an EMS based system be utilized for correcting slouching, AWD, and ILP ?
3. Can EMS based physiological feedback loops deliver equal or better user experience (accuracy perception, task disruption, engagement, comfort) compared to traditional feedback types (visual, audio and vibro-tactile)?
4. Will users prefer an automatic poor posture detection and correction system over alternative traditional feedback systems requiring self-correction?

### **1.7 Objectives**

The main objectives of our work include:

1. Design and development of sensor based automatic poor posture detection systems for detecting slouching, AWD, and ILP.
2. Design and development EMS algorithm for correcting slouching, AWD, and ILP through involuntary muscular contractions.

3. Integrate sensors and EMS with wearable technology for automatic detection and subsequent correction of slouching, AWD and ILP.

## 1.8 Contributions

The main contributions of our work on automatic posture correction utilizing EMS include:

1. Design and development of an automatic slouching detection and correction system utilizing EMS.
2. Design and development of an automatic AWD detection and correction system utilizing EMS
3. Design and development of an automatic ILP detection and correction system utilizing EMS
4. Four novel user studies for quantitative, and qualitative evaluation of performance, and usability of our automatic poor posture detection and correction utilizing EMS feedback against different traditional feedback techniques (audio, visual, and vibro-tactile), and under different conditions of posture awareness and engagement in breaking habitual poor posture.

## 1.9 Thesis Statement

*“Automatic posture correction using sensor-based detection and subsequent EMS induced physiological responses through active feedback loops results in faster correction at high accuracy in comparison to alternative traditional techniques (audio, visual, vibro-tactile), while simultaneously delivering an equally comfortable user experience.”*

## **1.10 Reader's Guide**

Chapter 2 is a compilation of the related works and the technological advancements in poor posture detection and alert mechanisms, and utilization of EMS in rehabilitation and HCI. Chapter 3 details our automatic slouching detection and correction system along with a human subject study conducted to compare performance of our approach against alternative traditional audio, and visual feedback systems. Chapter 4 details our automatic AWD detection and correction system along with a human subject study conducted to compare performance of our approach against alternative audio, and vibro-tactile feedback systems. Chapter 5 details our automatic ILP detection and correction system along with two user studies conducted to compare performance of our approach against traditional audio and vibro-tactile feedback systems. Chapter 6 details a discussion on the quantitative and qualitative results of our studies in each of the three use cases with additional focus on performance, user perception, and feasibility. Chapter 7 presents the limitations of our work and proposals for future work followed by the conclusion in chapter 8.

The next chapter focuses on the related work, and challenges faced in developing instrumented wearables intervention devices for enabling posture detection and correction.

## CHAPTER 2: LITERATURE REVIEW

### 2.1 Slouching

#### 2.1.1 *Slouching Detection*

Although there exists a prevalent approach to improve posture through ergonomic solutions such as adjusting desk and chair heights, monitoring viewing angles, and keyboard and mouse positions [9], there exists only a small number of reliable techniques for continued posture monitoring and detection of poor posture, especially slouching. With the increase in computational power, sensor miniaturization, and development of wearable technology, posture monitoring has been attracting increased attention for developing detection and alert-based wearables that allow the user to self-correct their posture based on feedback from the system. This development of sensors and their integration into wearables has also enabled real-time monitoring, and live feedback systems irrespective of the location of the work environment. Despite these efforts, and due to the novelty of wearable intervention technologies, current research is focused on developing more accurate monitoring techniques, and development of predictive algorithms for better detection of poor posture. As a result, aspects such as integration of embedded sensors into wearables, aesthetics, usability, wearability, and user comfort are often neglected.

Previous research on slouching posture monitoring is mainly focused on sensor-based and vision-based systems for monitoring and detection. The sensor based slouching posture detection techniques employ a variety of sensors such as inertial measurement units (IMU), force sensitive resistors (FSR), electromagnetic inclinometer, fiber-optic sensors, and smart garments. Vision-based systems often include the use of a camera and Microsoft Kinect for monitoring, detection, and alerting the users. Past research on posture monitoring and detection can be classified into two main categories:

slouching monitoring without feedback, and slouching detection with real-time feedback solutions.

### *2.1.2 Slouching Monitoring without Feedback*

Slouching posture monitoring is a domain of research primarily in the medical sector to investigate the causes of long-term health effects of poor posture at the workplace leading to chronic conditions of the spine such as kyphosis. DorsaVi's ViMove designed by Charry et al., was an ambulatory inertial system for 3D measurements of low back movements. They utilized an accelerometer, and a gyroscope placed on the upper, and lower spine regions to measure the 3D orientation of the spine [33]. The results of the spine position from their positional algorithm were validated by an Opti Trak system. Developing upon this, Kang et al., embedded IMU sensors into a smart garment to measure spine posture and compared them with a motion capture camera system [91] while Miyajima et al., utilized a six-axis accelerometer and gyro meter combination across the knee, hip, and spine to determine lumbar torque and validated their approach using an optical capture system [146]. The smart garment developed by Kang et al., employed a set of IMU sensors placed on the right and left shoulder, and on the right and left waist regions to determine pitch and roll motion for postural monitoring. Further, Voinea et al., proposed a model that converts orientation angles from the IMU sensors to calculate the curvature of the spine [196]. Their method involved the use of an instrumented shirt that fitted with 5 IMU sensors running along the spine from the upper to lower thoracic regions. Similarly, Hams et al., developed a smart garment that contained accelerometers placed along the spine, scapula, and shoulders to measure trunk inclination in children [77]. Building upon this, Felisberto et al., developed a wearable system for the elderly to classify good and poor posture while sitting by employing IMU sensors on the upper torso, hip, and legs [58].

Another approach employing a set of accelerometers was utilized by Wu et al., to design a vest



containing single axis accelerometers below the neck, chest, and left and right hips to determine tilt angles [206]. Additionally, Motoi et al., developed a wearable system with accelerometers and gyroscopes placed on the chest, lower thigh, and upper calf to monitor gait speed, and angular changes in the trunk, thigh, and calf muscles along the sagittal plane [148]. Building upon this, Cajamarca et al., designed "Straighten Up" to measure spinal posture and assessment of user experience [31]. The system contained accelerometers attached to the upper, central, and lower trunk. However, no accuracy or error rates were reported. Similarly, Faber et al., utilized the MTx IMU system to determine the optimal placement location for a single accelerometer to obtaining trunk inclination [55]. Alternatively, Tsuchiya et al., used a different approach by combining flex sensors with accelerometers to measure the shape of the lumbar skin and to identify lumbosacral alignment changes using X-rays [191]. Palmondon et al., used a similar technique by designing a hybrid system that employed IMUs and potentiometers at the pelvic and spine for 3D measurement of trunk posture [163]. Their study concluded that potentiometers are required when data from the magnetometers are unreliable due to ambient magnetic fields at offices. Further, Nath et al., developed a method to identify postural risks and trunk flexion using data from a smartphone's built-in IMU [152]. Alternatively, Tanaka et al., utilized an electromagnetic inclinometer on the chest, thigh, and leg for long term measurement of human posture [186]. Their method presented results with an angular resolution of 12 degrees. However, no accuracy or error was reported.

Spinal posture monitoring was also conducted by Bell et al., [18] and Dunne et al., [52] utilizing fiber optic goniometers to determine spinal and lumbar posture. While Bell et al., placed fiber optic goniometers along the L5 and S1 regions of the spine and pelvis to identify activities associated with the lumbar postures, Dunne et al., placed fiber optic goniometers along the spine and on the scapulae for monitoring seated spinal posture. The results indicated that motion profiles were accurately identified, and the system was comfortable and unobtrusive. However, no accuracy and errors were reported. Further, Bhattacharya et al., used an ergonomic dosimeter to develop a reliable system

for continuous monitoring of postural data in construction workers [23]. Their system measured postural angles of the torso and the upper arm in the sagittal plane. All the systems mentioned above are purely designed for monitoring and detection of spinal posture, however, the main limitation of these systems was the absence of a real-time feedback system for alerting or correcting the users' posture. The following section presents research conducted on detection and real-time feedback systems for spinal posture control.

### *2.1.3 Slouching Detection with Real-Time Feedback*

Slouching posture detection with real-time feedback is mainly an area of research associated with the development of wearable intervention technology for detecting poor posture and alerting the user to self-correct their posture. The three main types of feedback employed are visual, auditory and vibro-tactile through which information about the users' posture and the need to correct themselves is conveyed through visual messages/notifications on their monitors/smart phones, voice feedback, and vibration alerts respectively.

O'Sullivan et al., developed a real-time biofeedback posture detection system that employed a strain gauge along the spine to measure force exerted on the vertebra. They utilized auditory, and visual feedback mechanisms to analyze vertebral motion in the sagittal plane [158]. Similarly, Yan et al., designed a wearable system that employed IMU sensors on the back, and an IMU instrumented helmet to validate personal protective equipment for insecure motion warning using an auditory feedback alarm [208]. However, no data was published on the accuracy of the system. Further, Fathi et al., proposed a wearable system for detection of spinal displacement, and provide real-time alerts for hunched or slouched conditions [57]. They utilized Shimmer IMUs placed at the thoracic spine, cervical spine, and lower lumbar spine to detect spine displacement, but their real-time feedback system mechanism was not reported.

”Posture Monitor” developed by Abyarjoo et al., employed an IMU sensor that could be attached to the upper back of the users’ shirt for detection of poor posture and development of good posture habits using an auditory alarm [4]. However, the system was reported to be highly sensitive to postural changes and required further validation of the proposed system. Similarly, Valdivia et al., used an MPU-9250 IMU strapped to an elastic band worn at the waist [193]. They compared the performance of the IMU sensor with a Microsoft Kinect V2 by analyzing performance of the real-time feedback in an exergame that aimed at improving spinal posture. Their results concluded that though the IMU-based system performed more accurately than the vision-based Kinect system, the IMU-based exergame was less engaging to the users. Further, ”Zishi”, an instrumented vest developed by Wang et al., employed two 9-axis IMU sensors placed on the upper and lower spine for postural analysis, and alert using visual or auditory feedback through an android smartphone application [197]. However, their system was not validated and required further testing to establish its validity.

Building upon this, Wong et al., developed a trunk posture monitoring with an auditory alarm feedback system to estimate spinal curvature in the sagittal, and coronal planes using a tri-axial accelerometer, and three gyroscopes placed on the upper, middle, and lower regions of the spine [205]. The results indicated that trunk posture could be monitored with high accuracy during daily activities and were validated by a motion analysis system. However, they were unable to determine rotation of the trunk in the traverse plane due to the lack of magnetometer information in their system which is crucial to determine the lean and slouching conditions. Further, a proof-of-concept wearable system for postural balance, and gait training with real-time vibro-tactile feedback (vibration alerts) was developed by Xu et al [207]. Their system utilized eight IMUs placed on either side of the torso to monitor trunk tilt, and provide vibro-tactile feedback. However, limitations of their system included validation of the results, and determining rate of error for the system. Similarly, Gopalai et al., utilized a wireless IMU attached to the trunk, and a wobble board for providing real-time

biofeedback via vibrational alerts for postural control [67]. Their results indicated preliminary verification of the detection of poor postural control, and improvement in posture control when biofeedback was provided. The system was more focused on postural stability using biofeedback and less related to spinal posture detection.

Further, a hybrid posture alert system developed by Bazzareli et al., employed electromagnetic technology with a bi-axial accelerometer placed on the left and right scapulae, and provided vibro-tactile feedback to correct scoliosis in adolescents [17]. Their results indicated a good sensitivity of the system in alerting the users, however no accuracy was reported, and further testing for validation was required. Another approach was the use of inductive sensors by Sardini et al., to monitor seated posture, and validate with an optical measurement system [177]. Inductive sensors were attached to the front and back of a shirt to monitor seated posture, and real-time vibro-tactile feedback was provided for self-correction. Though the system was validated for detecting seated posture during different activities, only sagittal plane measurement of the spinal posture was taken into consideration.

”SPoMo”, a six-axis IMU with accelerometer and gyroscope was developed by Petropoulos et al., for automatic monitoring of spinal posture while seated [160]. The IMUs were placed on the lower and upper back, and provided vibro-tactile feedback to the users for maintaining upright spinal posture. A similar approach using IMUs on the upper and lower back was undertaken by Lou et al. They developed a smart garment fitted with IMUs (triple axis accelerometer and two axis gyroscope) on the upper and lower back regions for posture monitoring during daily activities, and subsequent vibro-tactile feedback for alerting users in case of poor posture detection [132]. However, both SPoMo and smart garment systems were affected by the accumulated error due to the gyroscope drift, and required additional calibration and filtering for long term utilization.

Another real-time feedback system, ”Spineangel” was developed by Ribeiro et al., to deliver real-

time audio feedback when poor posture was detected to enable the users to correct themselves. Their system employed a wearable belt fitted with a triaxial accelerometer to investigate the relationship between poor posture and lower back pain [171]. However, no results on the accuracy of the system and error rates were published. Further, Giansanti et al., also developed an auditory biofeedback wearable system that utilized accelerometers and real-time auditory feedback to improve postural control [64]. They utilized a uniaxial accelerometer, and three gyroscopes placed between the lower and upper spine close to center of mass of the body to determine the degree of flexion. An auditory sound feedback system that varied its pitch corresponding to the degree of flexion was delivered to the user to correct their posture. Though their study reported improvement in balance and reduced work expenditure for self-correction upon auditory alerts, their study was focused on postural control in elderly subjects and entirely relied upon auditory feedback. This may limit its use in elderly subjects with hearing deficits.

Further, Leung et al., designed "Limber", a minimally disruptive method for detecting poor posture and alerting in an office style workplace [115]. Their system incorporated IMU and strain gauges on the shoulders, spine, and neck to detect poor posture while sitting, and implemented a positive and negative feedback system based on correct and incorrect postures, respectively. However, no results were published, and no efforts were made to incorporate aesthetics, comfort, and workplace protocols into the proposed wearable technology. Alternatively, a real-time visual feedback approach was undertaken by Hermanis et al. Their proposed system utilized a 7x9 IMU grid attached to the back of a vest to monitor posture, and provided real-time visual feedback via an android application [81]. However, their system was not validated for accuracy. Another real-time visual feedback approach via a smart phone application was implemented by Lin et al. Their system contained a vest fitted with five micro-electromechanical triaxial accelerometers placed on the middle and lower spine, middle of the chest, and either side of the waist for real-time posture monitoring and feedback [118]. The wearable system was validated for functionality and aesthetics,

but limitations include testing of the system in elderly subjects only.

Finally, Millington et al., conducted a qualitative assessment of different commercially available wearables available for posture detection and correction through real-time feedback systems [144]. They compared the effectiveness of postural monitoring using the LUMO Lift (IMU: triaxial accelerometer, triaxial gyroscope and magnetometer), Lumo Back (IMU: accelerometer), and Prana (IMU sensor and breathing). The Lumo Lift delivered real-time feedback via haptic vibrations, while the Lumo Back and Prana delivered visual feedback via smartphone applications. Their study concluded that vibro-tactile feedback based on real-time monitoring enabled detecting poor posture and subsequently delivering real-time feedback to the user to correct themselves. However, all the above-mentioned posture detection and feedback techniques focus only on alerting the user through vibro-tactile, visual, or auditory feedback mechanisms, and require a conscious effort by the user to self-correct themselves. This places a cognitive load on the users engaged in a task and rely solely on the user's intent or desire to correct their posture based on the received feedback.

#### *2.1.3.1 Slouching Preventive Healthcare/Alert Mechanisms*

Currently, several different passive medical orthotic posture braces illustrated in Figure 2.1 are available for purchase. However, they primarily focus on maintaining posture during every day at-home, and work activities, and must be worn at all times. Although they prevent poor postures in the users, they do not dynamically detect and correct poor slouched posture and are not aimed at reversing slouching postural degeneration.



Figure 2.1: Passive medical orthosis braces for posture correction.

The above literature on slouching detection presents a gap in research for the design and development of an autonomous slouching detection and correction system for dynamically correcting slouched posture, and preventing poor slouched posture for maintaining good spinal health.

## 2.2 Asymmetric Weight Distribution

Owing to increasing awareness of workplace injuries, and health and wellness, there has been a renewed interest on the relationship between postural control and cognitive load in recent times [10]. Although, postural sway corrections to certain extent are affected automatically and not consciously in response to visual, vestibular, and proprioceptive information, additional cognitive load demands for extra resources, and balance monitoring and correction techniques [11, 97, 107, 138, 187]. Previous research on AWD monitoring and detection can be classified into two main categories: Balance and stability monitoring, and AWD detection with real-time feedback solutions.

### *2.2.1 Balance and Stability Monitoring*

Balance and stability monitoring has primarily been an area of research for detecting neurological disorders, gait imbalance, and injury and post-surgery rehabilitation. Traditionally, the measurement of impaired balance and AWD employed highly specialized equipment such as force plates [13, 80], electrogoniometers [157], video motion analysis [44], electromyography [142] and magnetic tracking systems [183]. Balance and stability monitoring techniques using force plates often measure the center of pressure/gravity, while IMUs, and video analysis techniques rely on computed angular changes. However, the expensive equipment developed for medical rehabilitation, and clinical research was found to be cumbersome due to the attachment of markers and sensors to the skin/clothing. This resulted in difficulties in conducting easy, non-invasive data collection with respect to AWD.

There have been numerous studies on postural sway, and standing balance monitoring using force plates. Force plates contain an array of load/pressure sensing load cells or pressure sensing elements to monitor postural sway. Goldie et al., evaluated the reliability, and validity of force plates by investigating steadiness in four different stances (two-legged, step, tandem and one-legged), and concluded that the center of pressure (COP) was the best predictor of steadiness [66]. Further, Le Clair et al., assessed the repeatability of force plate postural stability measurements using COP in open/closed eyes, five different test durations, and one/two-legged stances, and found that postural sway increased with test duration [110]. Developing upon this, Benvenuti et al., investigated severity, and nature of postural disturbances during quiet standing positions in patients [19]. Their study indicated that COP measurements using force plates could expose impairments leading to disequilibrium, and evaluate compensatory strategies. Additionally, Prado et al., utilized force plates to investigate the effect of dual tasks (staring at a blank target, and counting letters) on standing balance among young and older adults by investigating the COP displacement [166]. Their results



indicated that performing dual tasks had a significant effect on postural sway in older adults. Further, Stoffregen et al., investigated body sway on land and sea [183].

Standing balance has also been evaluated using a Wii Balance Board (WBB) by Clark et al., where they compared postural sway using the center of gravity (COG) and center of pressure in different conditions such as one-leg stance, two-leg stance, and open/closed eyes. Further, Gil-Gomez et al., and Young et al., also evaluated standing balance using the WBB. While Gil-Gomez et al. conducted a clinical trial in brain injury patients to determine the effectiveness of balance rehabilitation [65], Young et al., assessed standing balance in older adults for prediction of fall risks [209]. Additionally, other researchers also investigated postural sway and standing balance in a quiet standing condition among young [12, 117, 162], elderly [16, 47, 48], athletes [104, 112], and patients [61, 173, 188].

Alternatively, the wide availability, and low cost of IMUs have enabled researchers to employ IMUs for monitoring postural sway, and AWD in clinical rehabilitation for patients suffering from Parkinson's disease (PD), and diagnosing sports-based impairments. Baston et al., investigated the effects of altered postural control, and balance on the ankle and hip in PD patients [15]. They utilized two Xsens MTX IMUs placed on the lower spine, and right shank to quantify postural control strategy of the participants in quiet standing (30 seconds) tasks. Their results indicated that posture correction through the ankle adjustments was preferred by the participants. Building upon this, Bonora et al., conducted an instrumented one leg stance (OLS) test to investigate anticipatory postural adjustments in patients with PD [27]. They positioned three Opal APDM IMUs on the lower spine, and right and left legs to monitor the change in acceleration and angular velocity. Their study concluded that a wearable system of IMUs could potentially be utilized for quick balance assessments in clinical settings. Further, Pollind et al., developed a low-cost MEMS based IMU wearable for sway assessment and detecting balance impairments [164]. They utilized ICM-20498 IMUs placed on the knees and feet to assess static balance in open/closed eyes conditions. Their results indicated that postural sway was greater in an eyes-closed condition. Postural sway has also

been studied in athletic populations for diagnosing balance impairments. Alternatively, Grafton et al., utilized a wireless IMU-based head-mounted wearable for detecting irregularities in athletes at risk of AWD [70]. Their study showed that IMU-based systems can be utilized to quantify balance impairments and head impacts in different populations.

Further, Guo et al., evaluated the accuracy of IMUs for measuring base of support, and the effect of task complexity on the accuracy [74]. They utilized Xsens MVN BIOMECH system with 17 IMUs placed on the head, shoulders, upper arms, forearms, pelvis, upper and lower legs, and feet. Their results indicated that the accuracy of the IMU system in detecting postural sway had an error ranging between (-12.6 % to +64.6%). Postural sway and balance impairment studies have also been conducted by different researchers for postural control in concussion patients [45], neurological disorders [211], and injury prevention [170]. However, the above-mentioned research studies are focused only on the assessment, and monitoring of balance and postural sway for diagnosis of balance impairments, and development of rehabilitation protocols for balance training and not on providing posture correction feedback to the users.

Computer vision-based systems have also been employed by researchers for video analysis of clinical research footage to analyze and diagnose postural sway, and imbalanced gait in patients [86, 92]. Gait analysis studies have also been conducted by different researchers for gait recognition in 2D [84, 212], and 3D [22, 143] using expensive cameras, and markers placed on the users. Recently, the emergence of low-cost depth cameras has enabled a renewed interest in their utilization in gait monitoring, and rehabilitation. Maudsley et al., utilized a Microsoft Kinect to detect postural sway by using the skeletal output for determining the center of mass of the user [137]. Their results indicated that static balance assessment in open/closed eyes using the Microsoft Kinect performed equally well in comparison to a clinical posturography system (NeuroCom SMART balance Master). Similarly, Clark et al., conducted a study to assess the validity of the Microsoft Kinect in detecting postural sway [35]. Their study validated the Microsoft Kinect against a multiple-camera 3D motion

analysis system in different postural control tasks such as forward reaching, lateral reaching, and eyes closed OLS. Further, the Microsoft Kinect has also been utilized by Mazumdar et al., for developing a screening tool for assessment of stability in geriatric patients [140], and by Barry et al., for developing exergames for postural control in healthy adults [14]. However, the limitations of computer vision-based technologies include occlusions, noisy environments, and tracking multiple humans.

### *2.2.2 Asymmetric Weight Distribution with Feedback*

Maintaining balance and stability is a complex activity that is accomplished by a synergy between the brain, and different sensory information from the vestibular, somatosensory, and visual systems. Postural instability or abnormal postural sway coincides with asymmetric weight distribution or weight bearing asymmetry when feedback from sensory systems is inaccurate. However, this loss or absence of sensory information can be compensated by providing additional external sensory feedback to the brain for effecting posture correction, and maintaining balance [82, 147]. Due to the advancements in sensor technology, and smarter algorithms, the past decade has seen an increased interest in the design and development of biofeedback based postural control devices for maintaining balance. This has led researchers to develop wearable posture control systems which primarily focus on improving effectiveness of postural feedback, usability, and portability [88].

Dozza et al., developed an audio biofeedback system for improving balance in patients suffering from bilateral vestibular loss [50]. They presented users with a generated stereo sound that encoded the COP with respect to the postural sway obtained from a AMTI OR6-6 force plate. In a quiet standing task with eyes closed, when users swayed left or right, audio feedback with increasing pitch and volume was presented to the participants to the respective ear via over-the-ear headphones, and required the users to self-correct, and restore their balance. Their results indicated that their system

was able to reduce the sway area by 23%, and increased the time duration of the users in a balanced state by 195%. Additionally, they also utilized stabilogram diffusion analysis and EMG activity to support their hypothesis that audio feedback would be able to actively help the brain with increased postural awareness for maintaining balance [49]. Building upon this, they further compared the effect of visual senses, and environmental conditions on postural control [51]. They tested the users under different conditions such as with/without audio feedback, open/closed eyes, and firm/foam surface, and concluded that audio feedback was utilized by the brain differently depending on the environmental conditions, and visual information for controlling postural imbalance. Balance improvement using audio feedback was also investigated by Chiari et al., where they developed an IMU-based wearable prototype [34]. Their prototype monitored the trunk position and delivered a varying auditory tone corresponding to the postural sway to the users via headphones in real-time. The audio tone varied in its modulation, frequency, and volume corresponding to the sway in the users' trunk position. Their results in a quiet standing task showed that users' balance greatly improved by their audio biofeedback prototype in comparison to absence or unreliable sensory feedback. Further, Santarmou et al., developed an audio feedback prototype insole embedded with pressure sensors for improving balance and postural sway in a balancing task on a wooden roller with open/closed eyes [176].

Effectiveness of human balance improvement was also investigated through visual feedback by Halicka et al., using force plates, and IMUs placed on the lower spine to monitor the trunk position [75]. Their visual feedback approach was investigated in a quiet standing task where a moving red point corresponding to the users' sway was displayed in a 2D graph on a monitor, and users were required to control postural sway, and maintain balance such that the red point was stable and at the center of the monitor. Their results confirmed that visual feedback had a stabilizing effect while decreasing body sway by activating voluntary postural control for maintaining balance. Further, Grewal et al., studied the effect of interactive balance training based on IMU sensors, and

visual feedback on postural stability in daily physical activities in diabetic patients over a 4-week period [72]. The users' COP, ankle and hip joint sway were monitored with Biosensics LegSys during a virtual game. The users were required to shift their weight to move a virtual marker to reach and cross virtual objects in the game. Their results showed a significant improvement of postural balance using wearable sensors, and visual feedback training. Developing upon this, they developed a balance rehabilitation strategy based on ankle movement to compensate for impaired joint proprioception in diabetic patients [73]. Their findings showed higher training gains in postural stability through the integration of IMUs, and visual feedback systems.

Augmented sensory feedback through visual, and auditory bio-feedback was further explored by Hasegawa et al., to investigate relative effectiveness of the two types of feedback on improving postural control [78]. Their study monitored the COP from a force plate when users swayed forward and backward corresponding to a target moving in sinusoidal fashion. While visual feedback was presented by increasing or decreasing the size of a target when the user was further or closer to their COP, auditory feedback was presented by increasing or decreasing volume when the user was further or closer to their COP. Their results concluded that audio feedback was more effective in comparison to the visual feedback for motor learning, and maintaining balance. Researchers have also explored the use of virtual reality in developing balance training rehabilitation protocols, and biofeedback for minimizing fall risks [98, 195], improving standing balance in patients suffering from hemiplegia [24], and PD [63]. While Virk et al., developed virtual reality strategies to minimize fall risks through visual feedback, and training [195], Keshner et al., investigated the influence of moving visual immersive environments on postural control and balance [98].

However, all the above-mentioned balance and stability detection techniques focused on alerting the user through audio or visual feedback and relied entirely on the users' ability to process the feedback, and their willingness to self-correct their AWD. Although, these AWD detection techniques enabled minimization of postural sway, and restoration of balance using different types of feedback, no

posture correction feedback response times, and user perception parameters have been reported. They also place a cognitive load on the user by relying solely on the user's intent and desire to correct their posture based on the received feedback. This presents a gap in research for the design and development of an autonomous AWD detection and correction system for preventing fall risks, gait imbalance, and proper rehabilitation after injury and surgery.

## **2.3 Improper Loading Posture**

Previous research on improper loading posture monitoring, and detection can be classified into two main categories: improper loading monitoring and detection without feedback, and improper loading detection with real-time feedback solutions.

### *2.3.1 Improper Loading Monitoring and Detection Without Feedback*

A system for monitoring, detecting improper lifting habits, and providing correctional feedback would greatly benefit workers and employers. Improper loading posture detection and analysis has primarily been a domain of research in occupational therapy for investigating ergonomics of worker safety, and health. Researchers have utilized computer vision, and IMU-based monitoring systems to track workers posture to obtain important information about the workers torso, knees, and ankles during different lifting activities.

Ergonomic monitoring systems using computer vision have been developed by researchers for preventing lower back injuries, and supporting proper loading posture while lifting. Wells et al., developed an automatic visual tracking algorithm for analysis of lifting techniques [199]. The main components of their algorithm included silhouette extraction, torso identification, lift characteristics, and classifying proper and improper lifting technique. Their algorithm analyzed video sequences

from different lifting scenarios and concluded that system performance decreased with size of the objects being lifted. Alternatively, Greene et al., utilized computer vision for estimating trunk angles during lifting [71]. Their method analyzed moving images of lifting, and extracting features for estimating angular acceleration of trunk flexion during lifting actions. Their training sets were synthetically generated based on mannequins representing a range of loading postures and were validated against human posture data obtained from synchronized video recordings of motion capture systems. Their results indicated limited precision as the difference between the predicted and the motion captured data showed a difference of  $14.7^\circ$  for the trunk angle. Similarly, Mehrizi et al., developed a deep pose estimation algorithm for predicting lower back load during lifting activity [141]. Their framework evaluated different lifting data sets to capture full 3D body pose using a deep neural network and estimated the body pose by calculating the force exerted on the lower back. Their approach performed equally well against expensive marker-based motion capture systems, and demonstrated the viability of their system for bio-mechanical assessment of occupational lifting. However, these systems utilized post-hoc algorithms to the images, and video footage and hence do not provide any real-time feedback to the user.

Computer vision-based tracking systems have also been developed for tracking improper loading posture for manufacturing, industrial workers, and for healthy living at home. Martin et al., developed a training protocol to analyze employees' current lifting, and carrying methods using a Microsoft Kinect. Their training protocol measured strain on workers' torso and recommended safe lifting weight limits [135] to the users. Additionally, Delpresto et al., utilized a Microsoft Kinect to develop an adaptive training system for factory workers to lift weights in a safe manner [42]. They utilized the Kinect's skeletal, and joint tracking abilities to observe human lifts, and provide recommendations on proper lifting techniques based on bio-mechanical models to maximize safety. Their system tracked 7 body parts- knee, hip, spine, elbows, feet, hands and neck and determined safe lifting angles with hip bend ( $45 - 90^\circ$ ) and knee bend ( $< 90^\circ$ ). Although they developed a

real-time tracking system, their system relied only on delivering safety recommendations for further lifting. Developing upon this, Zhao et al., developed a Kinect based system for encouraging healthy posture at home [213]. Their system integrated the Kinect tracking with wearable computing devices to enable tracking of users' activity and detecting poor postures that could lead to back injuries and/or sedentary conditions that could contribute to unhealthy lifestyle. Their system computed torso inclination angles from the skeletal, and joint information to detect poor loading posture, and delivered real-time alerts to the user via their smart watch when poor postures or inactivity was detected. However, all the above-mentioned visual tracking systems do not provide any correctional feedback to the user and are expensive to setup, time-consuming in process, sensitive to occlusions, field of views, and surrounding environment.

IMU-based wearables have also been utilized for investigating into work-related musculoskeletal disorders surrounding the lower back. The limitations of the vision-based systems such as occlusion, and cost have been overcome by the low cost wireless IMUs. A real-time IMU-based self-awareness system was developed by Yan et al., for assessing high risk postures, and warning workers while performing hazardous operations [208]. Their system integrated wireless IMUs with workers' helmets, and safety vests to track the head and torso movements, and delivered real-time feedback via a custom smartphone application. However, the proposed method was only tested in a small population and feedback correction response times, and user perception parameters were not investigated. IMU-based systems have also been utilized to automatically classify different ways of picking up objects, object positions, and walking while carrying objects using supervised machine learning algorithms [69]. They developed a wearable vest with embedded Xsens MVN IMUs along the trunk, biceps, and forearms. Additionally, they placed IMUs on the thighs, legs, and in a headband on the forehead. Their algorithm differentiated between frontal, unilateral, and side load positions with an accuracy of 96%. Further, O'Reilly et al., also developed an IMU-based tracking system for assessing body weight squat techniques and for delivering exercise performance feedback



to the users [156]. To extract squat features for detection of poor posture, they utilized Shimmer IMUs on the lower spine, thighs, and legs, and reported an improper squat posture detection accuracy of 80%. Although, their system was able to detect improper squatting posture, their system does not provide the feedback directly to the user in real-time.

Reducing risk of improperly lifting loads through wearable IMUs and machine learning have been evaluated by different researchers [29, 38, 114, 152, 192]. Conforti et al., proposed postural pattern recognition using machine learning, and IMUs placed on the thighs, shin, feet, and upper and lower spine, to classify improper and proper loading posture using different weights [38]. Nath et al., developed a low-cost body posture monitoring technique for identifying potential work-related ergonomic risks using smartphone sensors [152]. While Conforti et al, classified improper loading postures with an accuracy of 99.4% utilizing a supervised machine learning algorithms on the measured trunk kinematics and range of motion of lower limbs, Nath et al., measured trunk and shoulder flexion to demonstrate applicability of their approach for workers in various occupations. Building upon individual worker posture monitoring, Valero et al., developed a data processing framework for delivering diagnostics on worker posture, and health risks based on IMU information from a group of workers in an area [194]. Their system illustrated the use of machine learning, and data processing of motion data acquired from a group of individuals to assess high risk working postures under demanding circumstances.

To understand the physical, and bio-mechanical demands of various construction related tasks, and their effect on lower back disorders, Umer et al., compared differences in lumbar biomechanics during stooping, one-legged kneeling, and squatting [192]. They developed a hybrid posture monitoring system using electromyography and accelerometers. They placed accelerometers along the trunk and surface electrodes to measure the trunk kinematics and muscle activity respectively. Their results indicated that stooping demonstrated a reduction in the lumbar muscle activity which may cause a shift in loading to the passive spinal structures, and a high-risk factor for development

of lower back disorders. Further, Brandt et al., also developed a hybrid improper posture loading detection technique using surface electromyography, and accelerometer measurements on the trunk to classify lifting techniques in to low and high-risk categories [29]. While the accelerometers placed on the upper and lower spine monitored the trunk inclination, the surface electromyography electrodes were placed on the trapezius, and erector spinae to monitor muscle activation during lifting tasks. However, their system was only able to deliver a classification accuracy of about 65%. Although IMU-based systems solve the issues of occlusion, and are relatively less expensive compared to visual based technologies, the above-mentioned studies focus primarily on obtaining diagnostic information on improper loading posture, gait for developing preventive awareness, and rehabilitating protocols for occupational hazards.

### *2.3.2 Improper Loading Posture Detection with Feedback*

Although several studies have examined the trunk, hip, and knee stability during occupational lifting, and classified improper loading postures, relatively few studies have dealt directly with providing correction feedback to the user. An IMU-based Smart garment was developed for patients with spinal disorders to help facilitate rehabilitation therapy by providing continuous posture monitoring, and a real-time audio feedback when a poor loading posture was detected [204]. Their study indicated that their approach had a high accuracy with less than 1° error in detecting poor loading posture in static and dynamic lifting positions. Additionally, their study also indicated that their smart garment enabled patients to reduce time spent in poor postures by at least 40%. Similarly, “Lift Alert” was developed by Safety Alert Systems, to provide postural biofeedback to the user [54]. Lift Alert, a small battery-operated device worn on the users’ collar contained a mercury switch with five different sensitivity settings to detect trunk angle, and provide an auditory feedback tone when poor trunk posture is detected. Although the study concluded that Lift Alert was reliable in detecting trunk flexion angles, their system addressed only a single component of safe lifting i.e.,

only trunk flexion while the knee position which also plays a crucial role in safe lifting, was not considered.

Alternatively, real-time vibro-tactile feedback for correcting poor posture has also been investigated by researchers. An analysis of ergonomic human lifting behaviors was conducted using “CareJack”, an IMU-based vibro-tactile feedback system designed for detecting poor loading posture, and presenting correction feedback to the user [106]. Their system classified ergonomic, and unergonomic lifting movements using the angular acceleration, and velocity from the 5 IMUs placed on the users’ spine. Their study also evaluated the effectiveness of their classification for slow (4.5 *seconds*), and fast (2 *seconds*) lifting movements. Although their system was able to provide feedback using a vibro-tactile belt when improper loading postures were detected, posture correction still relied completely on the users’ willingness to correct their posture. Other limitations of their system include a small study population (8 participants), and performance of the classifiers. Even though the above-mentioned feedback techniques using audio and vibro-tactile modalities have been known to improve posture by mitigating the incidence of improper loading posture, and reduce the time spent in poor posture, they still relied on the speed of correction feedback presented to the user, the users’ readiness, and desire to correct their position when feedback was presented.

This has led researchers to also develop passive, and active lift assist wearable exoskeletons for preventing improper loading posture, and effecting controlled lifting strategies, respectively. Passive exoskeletons have been designed using spring-based mechanisms to store energy during the lowering phase of a lift, and leverage the stored energy to support the lifting phase of the lifting activity. These systems have proven to be effective in reducing stress and strain on the spine, and lower back while performing lifting activities [1–3, 131, 136, 198, 200]. Despite the effectiveness of the passive exoskeletons, their limitations include lack of versatility for different lifting tasks, and unreliable force and torque generation in the systems. These systems are also known to hinder movement during normal daily activities such as walking, and could cause increased leg muscle

activity, discomfort, and deconditioning [40].

To address the limitations of passive exoskeletons, researchers designed and developed active exoskeletons to mitigate the risk of spinal, and lower back injuries. Active exoskeleton systems developed for lift assistance, and increasing the versatility employed control systems, actuators, and external power sources for mitigating risk of injury by preventing improper loading posture [8, 89, 99, 100, 116, 149, 151, 186, 210]. These systems were able to demonstrate reduced effort, stress, and strain on the back muscles [116, 149]. However, these control systems are not autonomous, and cannot detect the users' intentions prior or during the lifting activity which does not enable them to activate or trigger the delivery of feedback to the actuators at the right moment. Power assistance through these exoskeletons is usually triggered manually using extra buttons or joysticks. Kobayashi et al., employed two buttons to control pneumatic actuators [101]. The button controller was embedded into the user's belt to enable the user to reach and trigger the power assistance when performing a lifting activity. Building upon this, Muramatsu et al., employed two switches on the users' fingers to enable control of the power assistance systems [149]. Although these approaches simplified the operation of exoskeleton systems, they had certain limitations. First, extra devices need to be placed on the users' body which increases the physical load on the user while performing an already demanding lifting activity. Second, these devices require manual control of the actuators which places an additional cognitive load on the user, and inconveniences the user. Third, this approach makes the lifting tasks intermittent, and reduces the work efficiency, and acceptability in work environments. Finally, most active exoskeleton systems require triggering the actuators manually, and may cause mistaken operations while lifting heavy loads.

In summary, the majority of these wearable exoskeleton systems have relatively bulky form-factors making them less practical for at-home daily use, or use in other business, and social settings. These exoskeletons are often designed with components that protrude along the length of the spine and legs which can interfere with common daily activities (e.g., sitting, climbing stairs, and work or

home environment navigation). Further, users are generally required to wear these exoskeleton systems conspicuously over their clothing, which can be undesirable. For all these reasons, the development of autonomous improper loading posture detection and correction system capable of automatically detecting improper lift posture as soon as it starts and subsequently correcting this posture can turn out to be crucial. This presents a gap in the research for developing an autonomous detection and correction of improper loading posture during lifting activities to mitigate the risk of injury to the lower back, knees, and ankles.

#### **2.4 Electrical Muscle Stimulation (EMS)**

Electrical Muscle Stimulation is a non-invasive technique for delivering pre-programmed trains of electrical stimuli to muscles, nerves, and joints via surface electrodes positioned on the skin to deliver an acute/chronic therapeutic effect. Traditionally, electrical stimulation was utilized for therapeutic pain management to alleviate chronic muscle strain, acute muscle spasms, and in rehabilitation to regain muscle strength, and normal movement after injury or surgery. Depending on the stimulation characteristics, and location of the electrodes, three main electrical stimulation modalities exist:

1. *Trans-cutaneous Electrical Nerve Stimulation (TENS)* employs the application of continuous, low-intensity electric current to the cutaneous nerve fibers. This modality does not target muscles and mainly used for acute and chronic pain treatment alleviating pain during and after stimulation therapy.
2. *Neuromuscular Electrical Stimulation (NMES)* involves the application of intermittent high-intensity electrical stimulation to generate strong bursts of muscle contractions. This modality is mainly used for neuromuscular rehabilitation/strength training ,and the benefits are experi-

enced after numerous repeated sessions.

3. *Functional Electrical Muscle Stimulation (FES)* utilizes the application of a cyclical moderate intensity electrical stimulation to selected muscles for physiological responses. This modality is mainly used for generating functional movements that resemble voluntary muscle contractions, and to restore functions that have been lost through injury, surgery, or muscle disuse. The electrodes are strategically placed above specific motor points that are responsible for limb movement, which allows invocation of an involuntary physiological response through muscle contraction and relaxation patterns. The benefits are mainly obtained during stimulation, and improve muscle memory in the long term.

#### 2.4.1 *EMS in Rehabilitation*

EMS was primarily used in rehabilitation [28] to assist disabled or paralyzed people in restoring motor functions such as hand grasp, walking, swallowing, standing, and obstacle avoidance. EMS was utilized in rehabilitation therapy to rejuvenate injured muscles or to enable muscle activation after surgery [184]. De Marchis et al., utilized functional electrical muscle stimulation (FES) for developing rehabilitation protocols to evoke hand opening through muscle synergies [41]. Popovic et al., developed an FES rehabilitation system for neuroprosthesis control to enable patients with spinal injuries to regain hand grasp, and walking functions [165]. Whereas Riebold et al., utilized FES intra-muscularly to target larynx to stimulate reflexes while swallowing in patients with dysphagia (Swallowing disorders) [172]. FES was also utilized by Previdi et al to develop rehabilitation training programs for standing up and sitting down in patients suffering from spinal injuries [167].

The past decade has witnessed novel interaction systems integrated with EMS for Human-computer Interaction (HCI) research. However, applications of EMS in HCI are different and primarily designed and developed to present spatial interaction techniques through involuntary muscular

contractions on the user's body based on computer feedback. This section focuses on the applications and interaction techniques based on EMS from the HCI community.

#### 2.4.2 *EMS in Human Computer Interaction*

EMS which has traditionally been utilized for rehabilitation therapy in patients after injury or surgery to regain muscle strength and function, has found new interest in Human computer interaction (HCI) for applications in gaming, augmented reality, and virtual reality training [102, 119–122, 181]. This presents an opportunity for developing novel interaction techniques using adaptive wearable interfaces. Interactive applications of the EMS technology can be classified in to three main categories:

- Activity Training
- Input/Output Interfaces
- Feedback based Immersive Technology

##### 2.4.2.1 *EMS in Activity Training*

- In *PossessedHand*, EMS was utilized by Tamaki et al., to enable learning physical skills such as playing string musical instruments [185]. They utilized EMS on the users' forearm to control the users' timing and speed of hand movements to help enable novice users to learn how to play musical instruments such as Piano, and Koto (Stringed instrument).
- In *Affordance++*, Lopes et al., demonstrated extending the affordance of objects by allowing the objects to actuate the users arm using EMS, and performing required movements when the user approaches the objects [126]. They demonstrated (i) actuating motion such as shaking a

spray can when touched before use, and (ii) staying away from cups filled with hot liquids. Their prototype integrated optiTrack (a vision-based system), and EMS to enable detection of the object and the position of users' arms, and subsequently stimulating the users' arms to provide affordance.

- In *Preemptive Reflexes*, Nishida et al., demonstrated the preemptive force feedback systems to accelerate human reaction time using EMS [93, 153]. They performed a psychophysics experiment by actuating the users' finger muscles to press the trigger to take a photo of a high-speed moving object. They determined that actuating the users finger muscles in a precise time window of approximately 80 ms prior to the users' actual reaction time allows the user to feel in control while capturing a photo of the high-speed moving object.

#### 2.4.2.2 EMS in Input/Output Interfaces

Adding input interfaces to EMS based system allows for the development of a closed loop input/output platform that enables a novel communication technique. Input/Output systems based on EMS are described below:

- In *Actuated Navigation*, Pfeiffer et al., communicated an EMS actuation signal to the sartorius (thigh) muscle to influence walking direction, and avoid obstacles, and uneven ground in a park with crowded areas ,and distractions [161]. Their results show that their system was able to steer the users left and right, thereby changing their walking direction by approximately 16° per minute.
- In *Muscle Plotter*, Lopes et al., developed a pen-based input, and EMS based output system to enable the user's hand to render curves in an interactive 2D wind tunnel simulation of a car [130]. The user requests a wind tunnel simulation by writing "Wind Tunnel" with an



anoto pen, and the muscle plotter computes the streamline of the simulation in response to a car sketch and responds by actuating the user's wrist with electrical stimulus. They also investigated the use of EMS in enabling the user to draw on an X-Y plot, and EC- Circuit simulator to plot the RC filter characteristics. Lopes et al., further developed "Let your body move" to demonstrate haptic feedback using muscle stimulation [127]. They developed a mobile application integrated with EMS to enable waving a user's hand.

- In *Notifications and Conversations*, Schneegass et al., devised "Embodied Notifications" a novel technique of gaining the users attention by utilizing the human body as a feedback channel to receive notifications [180]. They utilized EMS to communicate the source of the notification to the user from their smart device. Due to the nature of the notification feedback system being embodied and implicit, their system was able to effectively attract users to important information such as upcoming meetings reminders, and incoming messages by stimulating different parts of the body. On the other hand, Hanagata et al., developed "Paralogue", a remote conversation system using EMS [76]. The Paralogue (Parasitic + dialogue) utilized users arm and hand position to enable a remote conversation. One user's hand was fitted with a camera to record head positions (forward, backward, sideways, twist), and these were mapped to different hand poses in another user through EMS thereby enabling a remote conversation.
- In *EMS Painter*, Colley et al., developed an interaction technique to enable an audience to influence a painter, and co-create visual art works [37]. They placed EMS electrodes on the painter's arm and enabled integration with a tablet device controlled by the audience to cause deviation of the brush strokes.
- In *Raising Temperature*, Fortin et al., demonstrated the use of EMS to deceive users into perceiving a surface or object as dangerously hot even while it is below 50°C [60]. They accomplished this by inducing an artificial heat withdrawal reflex through involuntary con-

traction of the user's bicep immediately after contact with a virtual hot surface. Their results suggest that EMS could be potentially utilized to modify temperature perception in AR/VR applications and emergency response, and workplace training systems.

#### 2.4.2.3 EMS in Feedback based Immersive Technology

The above-mentioned interactive applications demonstrate that EMS provides more defined, implicit, and strong sensations than visual, auditory and haptic feedback mechanisms. These applications also exhibit miniaturization of feedback hardware compared to actuated motors in exoskeletons. EMS based feedback systems integrated with immersive technology are described below:

- In *Impacto*, Lopes et al., developed an EMS based application designed to provide the haptic sensation of hitting, and being hit in virtual reality. Impacto simulated a hit by decomposing the feedback stimulus in to tactile and impulse components [123]. The tactile aspect of being hit was simulated by employing a solenoid that taps on the user's skin, and the impulse of being hit was simulated by contracting the user's triceps and forearm backwards using EMS.
- In *Kinesthetic Feedback*, Nishida et al., developed a wearable stimulation device for sharing and augmenting kinesthetic feedback through EMS [154]. Their primary application is to facilitate virtual experiences of hand tremors in PD patients. They utilized EMS for providing shared experiences between users, and for preempting reaction times in users.
- In *Actuating Emotions*, Kono et al., developed "In-Pulse" which attempted to increase realism in virtual reality applications by inducing fear and pain [103]. "In-pulse" utilized EMS, and mechanical solenoid actuators in the design of a head mounted device to induce emotions such as fear and pain in virtual reality experiences. They integrated an Oculus with a solenoid placed on the forehead, and electrodes placed on the orbicularis oculi (facial muscles

responsible for closing eyelids) to invoke tactile feedback, and involuntary closure of the eyelids respectively in response to a punch delivered to the head by an avatar in virtual reality. Alternatively, Hassib et al., developed an "Emotion Actuator" to investigate the transfer of emotional states between users [79]. The System utilizes Electroencephalography (EEG) to interpret emotional states such as happy, sad, angry, and neutral from one user and transmits it to another user using EMS to generate an involuntary response. Their study revealed that participants liked the discreet sharing of emotions, and the embodied output using EMS to be more immersive in nature.

- In *Realistic Physical Experiences in VR*, Lopes et al., developed realistic physical experiences in VR by providing haptic feedback to walls, and obstacles [124, 128]. They utilized EMS to stimulate the user's forearm and triceps muscles in response to user interaction with wall surfaces in virtual reality. They also developed force feedback for mobile devices [130] by employing EMS to invoke involuntary muscular contraction to tilt the device sideways. The users perceive force feedback as they resist this motion with their other arm. They demonstrated this through a mobile game in which the users are required to steer an airplane through the winds simulated through EMS based force feedback. Further, they extended EMS based force feedback to mixed reality gaming where they added physical forces to virtual objects [129]. They demonstrated this through a mixed reality "balance the marble game" where the user had to move a virtual ball to a designated area. The user's forearm was stimulated to maintain or balance the ball on a tray. Similarly, Fabriz et al., utilized EMS to simulate impact in an augmented reality tennis game by stimulating the forearm muscles upon impact with a tennis ball to deliver a more immersive experience [56].
- In *Proprioceptive Interaction*, Lopes et al., developed "Pose-IO" that served as eyes-free interaction technique that allowed users to interact without visual and auditory senses and completely rely on proprioceptive sense [125]. Pose-IO demonstrated this by recognizing a

user's wrist gesture, and utilized EMS to stimulate their wrist muscles to generate the same pose involuntarily with an average accuracy of 5.8°.

The current literature suggests that postural correction utilizing EMS has not been fully explored, and thereby presents an opportunity for the development of wearable intervention technology based on EMS feedback for the detection and correction of slouching, AWD and improper loading posture. As part of this research, the following chapter details the design and development of an automatic slouching detection and correction system utilizing EMS.

## CHAPTER 3: AUTOMATIC DETECTION AND CORRECTION OF SLOUCHING



Figure 3.1: Improper posture can have long term health ramifications. Presented here are images of slouched and corrected posture using Electrical Muscle Stimulation: (A) Mobile Gaming - Slouched posture, (B) Mobile Gaming - Corrected posture, (C) Text Entry - Slouched posture, (D) Text Entry - Corrected posture.

Slouching is one of the most common sedentary poor posture affecting people from all walks of life. From the literature, the current intervention technology offers only slouch detection and requires users' conscious effort to correct improper slouched posture, and the interactive applications and adaptability of EMS based technology demonstrate its capability in delivering implicit, discrete, and more defined feedback compared to audio, visual and haptic feedback mechanisms. This has presented an opportunity for the design and development of a wearable intervention technology with automatic capabilities for slouched posture detection and subsequent correction through EMS based involuntary muscular contractions to restore healthy upright posture.

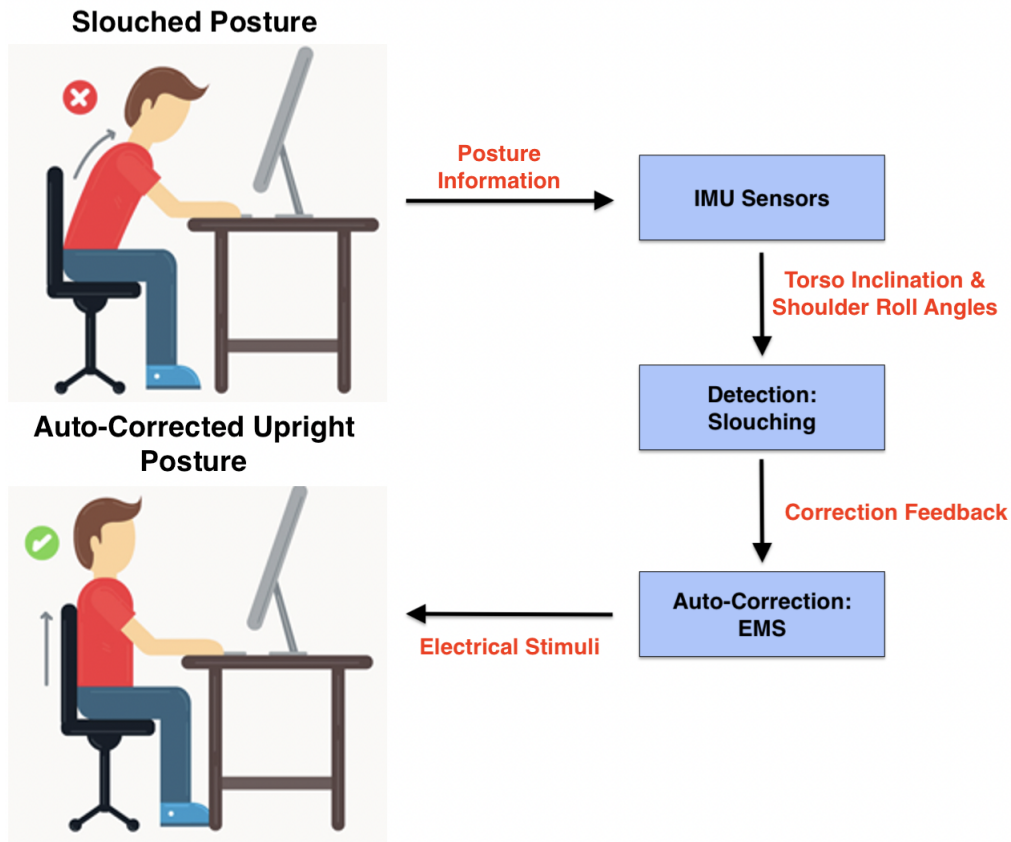


Figure 3.2: Physiological Feedback Loop: Automatic Slouching Detection and Correction System.

To address the problem of detecting and correcting slouching, we developed a physiological feedback loop-based wearable intervention prototype relying on IMU sensors and EMS (illustrated in Figure 3.2). Our prototype employed three Metawear MMC wireless sensors for measuring angular changes, and the *openEMSstim* package [121] for presenting the EMS feedback. We developed a user interface using the Metawear C# SDK and integrated the EMS hardware to complete the physiological feedback loop. As slouching was mainly characterized by torso inclination and forward rolling of the shoulders [90], IMU 1 was placed at the center of the collar bone above the chest (illustrated in Figure 3.3 (B)) and the other IMU's 2 and 3 were placed on the center of each deltoid (illustrated in Figure 3.3 (A) & (C)).

The change in posture was calculated from the angular information obtained from the IMU sensors. The user's torso inclination angle was calculated from the pitch of IMU1, and the roll angles on the shoulders were calculated from the roll of IMU's 2 and 3. Our system detected slouching when the user's current torso inclination and shoulder roll angles both approached and remained at a threshold level for a period of 5 seconds. The threshold level is preset as  $-3^\circ$  of the torso inclination and shoulder roll angles recorded in the slouched position during calibration.  $-3^\circ$  was chosen to overcome measurement errors without increasing false positives and a 5 second time duration ensured random movements do not lead to false positive slouch detection. These design choices were validated during our pre-study trials. The threshold angle of  $-3^\circ$  was used to initiate the 5 seconds timer, and the slouch angles detected were recorded at the end of the timer when the feedback was presented. The purpose of the timer was to ensure false positives due to participant behavior do not trigger the feedback response.

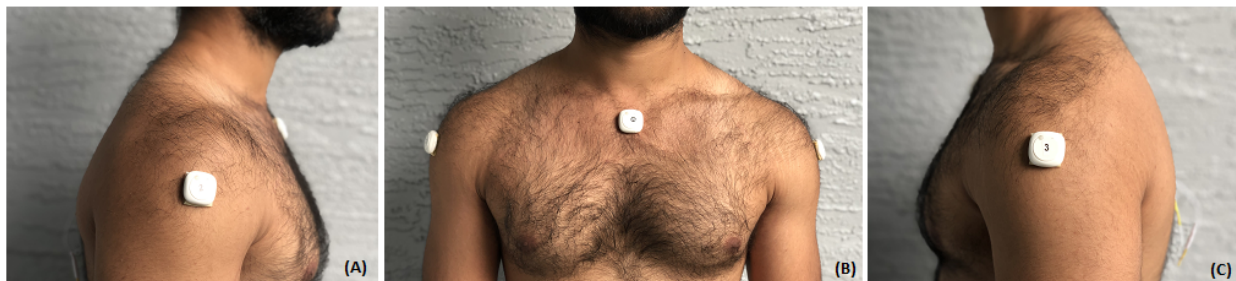


Figure 3.3: Wireless IMU sensor placement for posture monitoring and detecting slouched posture:(A) Side view showing sensor placement on left deltoid, (B) Front view showing sensor placement below center of collar bone above the chest, (C) Side view showing sensor placement on right deltoid.

### 3.1 Correction Feedback

When slouching was detected, the automatic correction feedback was presented by applying electrical stimulus to the rhomboid muscles (illustrated in Figure 3.4) for generating a pulling force in the opposite direction from the slouched posture and thereby, generating a physiological response to bring the user back to the upright or correct position. Two pairs of electrodes were utilized for contraction of the rhomboid muscles which causes the shoulders blades to be pulled back, thus unrolling the shoulders and bringing the torso back to the upright posture. IMU and EMS calibration play a crucial role in the effectiveness of the system. The calibration process included correcting IMUs offset value in the upright position of the user and recording the angular change in the slouched posture with respect to the upright position.

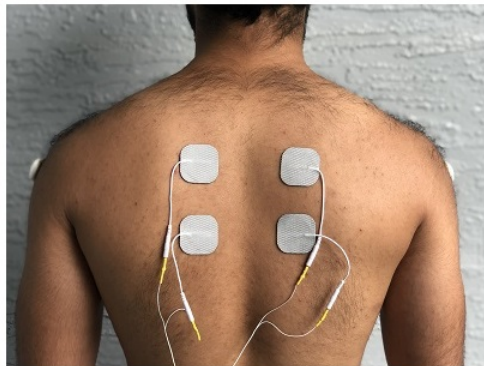


Figure 3.4: EMS electrode placement on rhomboid muscles for auto-correction using EMS feedback.

The EMS intensity calibration was manually incremented to deliver an intensity that was optimal for generating involuntary muscular contraction and avoid any pain. This EMS intensity provided to the user for generating the necessary pulling force for correcting the slouched posture and restoring the upright position was recorded and utilized during the experiment. The TENS device was able to deliver intensities between (0-100mA). A continuous 75 Hz square wave pulse at the recorded EMS



intensity and a pulse width of  $100 \mu s$  was supplied as the electrical stimulus to the users.

### 3.2 Operation

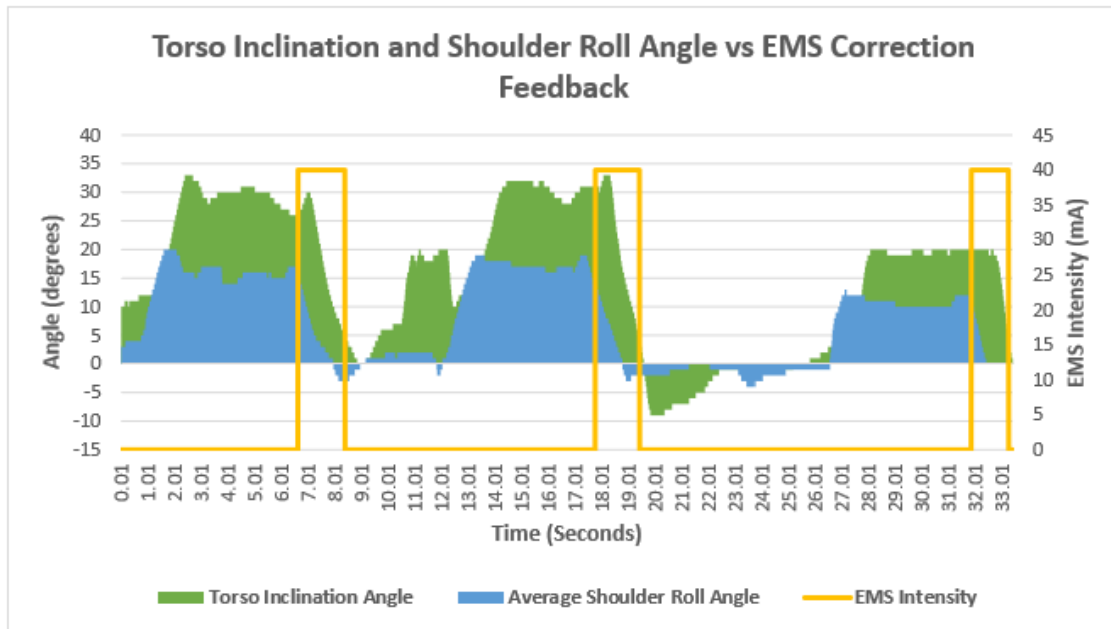


Figure 3.5: Automatic Detection and correction of Slouching: Graph showing EMS activation and deactivation. When torso inclination and shoulder roll angles cross the threshold and remain there for a duration of 5 seconds, EMS is activated. EMS is deactivated when upright posture is restored.

Figure 3.5 illustrates the activation and deactivation of EMS when slouched posture is detected and upright posture is restored during a test scenario. During calibration, the recorded torso inclination angle was  $23^\circ$  and shoulder roll angle was  $15^\circ$ , while the EMS intensity recorded for correcting slouched posture was  $40mA$ . When the current angles crossed the threshold of  $20^\circ$  for the torso inclination and  $12^\circ$  for the shoulder roll, the 5-second timer was initiated. Upon completion of the timer, if the current angles still remained above threshold angles, the EMS was activated to supply a stimulus of  $40 mA$  (recorded during calibration) to the rhomboid muscles to cause an involuntary

muscular contraction to restore the upright posture. The EMS was deactivated immediately after the upright posture was restored.

### 3.3 Methods

The goal of our study was to evaluate the overall effectiveness and user perception of an automatic slouch detection and correction feedback system (EMS) compared to traditional audio and visual feedback modalities requiring self-correction by the user based on audio and visual notifications, respectively. We also identified two common causes of slouching in day-to-day activities such as computer related workplace tasks, and mobile gaming [90, 159], and investigated our automatic approach using EMS across these common causes of slouching. Our objective was to determine if our automatic posture detection and correction system using EMS would be a viable technique for correcting slouched posture as compared to the visual and the audio feedback channels while being engaged in a computer related workplace task and playing a mobile game.

#### 3.3.1 Subjects and Apparatus

We recruited 36 Participants (Male=31, Female=5) for the study with 18 participants for each application- text entry and mobile game. All participants recruited were above the age of 18 years and the mean age of participants was 22.05 years ( $S.D. = 3.13$ ). All participants were able bodied and had corrective 20/20 vision. We used three Metawear MMC IMU sensors for monitoring the torso inclination angles and the shoulder roll angles. The EMS was generated with an off-the-shelf Tens unit and controlled by the *openEMSstim* package for activating and modulating the intensity of the electrical stimuli supplied to the muscles. The hardware used for the text entry application was a 14" Intel i7 Laptop, and a 2nd generation iPhone SE was used for the mobile game application.

From the pre-questionnaires, participants' ranking of their prior exposure to posture alert devices and EMS, and experience with posture problems and slouching are noted and illustrated in Table 3.1. Participants ranked their exposure and experience on a 7-point scale with 1 meaning never/no experience and 7 meaning frequently/very experienced.

Table 3.1: User ranking on posture awareness, devices, and EMS. User ranking on a 7-point Likert scale.

<b>User Experience</b>	<b>Application</b>	<b>Mean</b>	<b>S.D</b>
Exposure to posture alert devices	Text Entry	1.61	1.16
	Mobile game	1.89	1.09
Exposure to EMS	Text Entry	2.33	1.37
	Mobile game	2.06	1.43
Experienced posture problems	Text Entry	4.22	1.55
	Mobile game	4.33	1.49
Experienced slouching	Text Entry	5.06	1.50
	Mobile game	5.4	0.96

### 3.3.2 EMS hardware operation

The *openEMSStim* package used in this study contains an arduino Nano micro-controller which has the capability to control MOSFET switches utilized to turn on/off the EMS signals generated from a TENS device. MOSFET switches enable fast switching on and off of EMS signals and also allow for digital control for HCI applications. The *openEMSStim* package also contains a

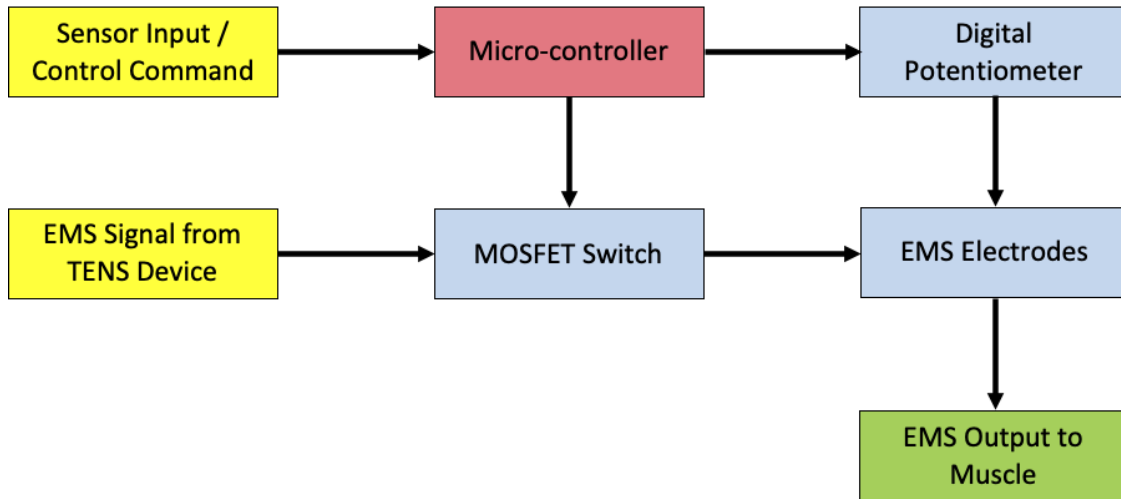


Figure 3.6: EMS Hardware Block Diagram.

digital potentiometer whose resistance can be varied to increase or decrease the intensity of the EMS signals from the TENS device. A system block diagram of the EMS hardware used in this study is illustrated in Figure 3.6. The *openEMSStim* package also has the ability to interface with sensors and computer/mobile based applications. In this case, we interfaced wireless Metawear IMU sensors with the *openEMSStim* package via a C# application.

### 3.3.3 Calibration Process

A step-by-step description of the calibration process is illustrated in the Figure 3.7. This calibration process was employed in all the human subject studies conducted as part of this research and determined optimal EMS intensity for delivering a smooth and comfortable experience to the user while invoking an involuntary muscular contraction and achieving the desired physiological response.

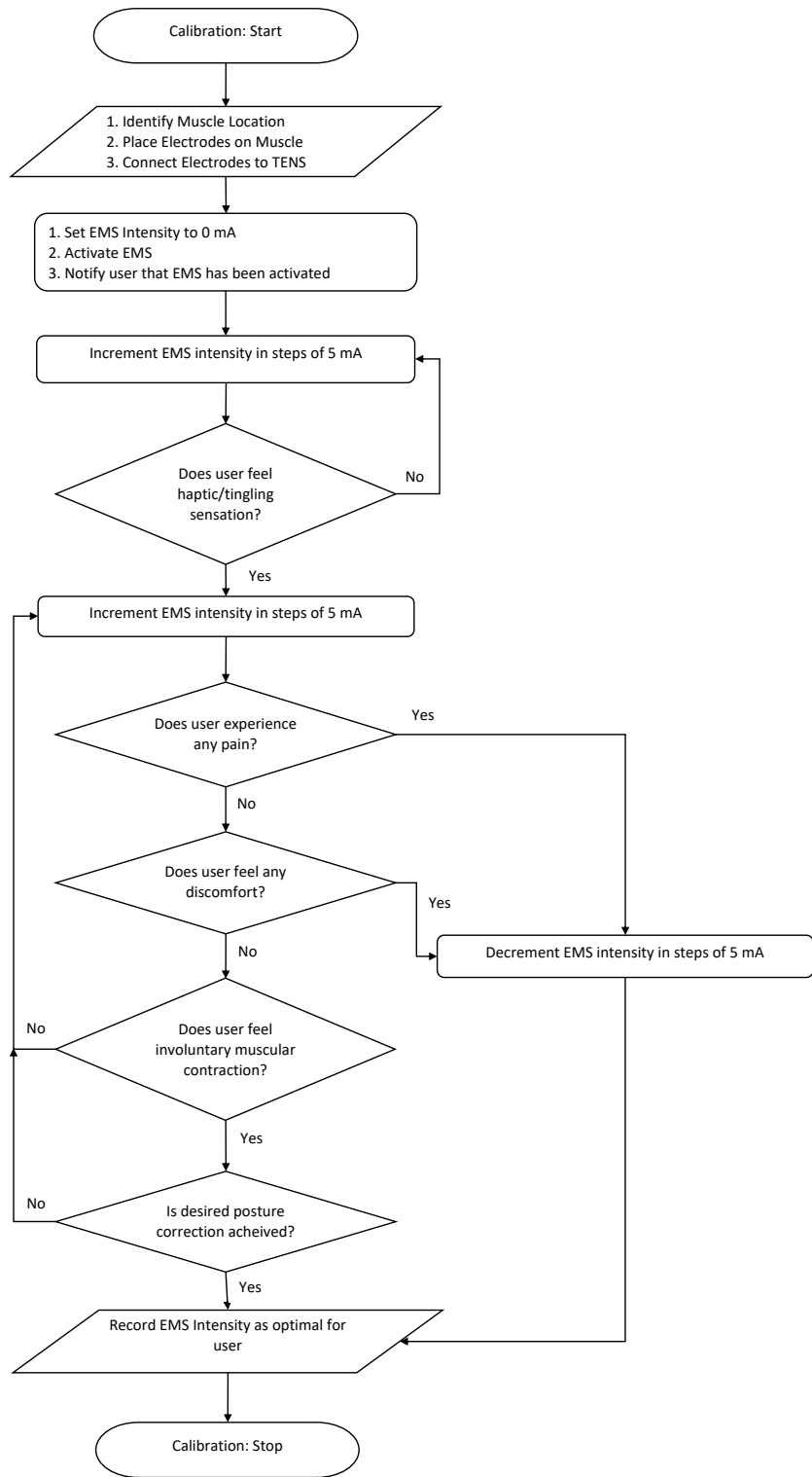


Figure 3.7: A step-by-step description of the calibration process for optimal EMS intensity

In the case of slouching, the desired physiological response was the torso stabilization. The calibration process was employed for the rhomboid in automatic correction of slouching. We employed an user-in-the-loop approach for calibrating the optimal EMS intensity where the user was required to verbally respond to the research moderators' questions during the calibration process. At each increment of the EMS intensity, the user was specifically required to respond to their level of comfort, indications of any pain in the stimulated muscle area, and if they experienced involuntary muscular contractions. When involuntary muscular contractions were experienced by the user, the moderator confirmed if the user was comfortable at this EMS intensity and if any pain was experienced. When the user was comfortable with the EMS intensity, no pain was experienced, and involuntary muscular contractions were achieved for desired posture correction, the EMS intensity was recorded for use in the EMS feedback part of the study experiment and the calibration process was completed.

### *3.3.4 Experimental Design*

A 2 by 3 mixed subjects experiment with 36 participants was conducted to investigate the performance and feasibility of our approach. The within subject factor was feedback type (visual, audio, and EMS) and the between-subject factor was application type (text entry, and mobile game tasks). We compared the performance of automatic slouching correction using the EMS feedback against the self- correction in the visual and audio feedback techniques. Average correction response times and user perception of the system across the two applications and three feedback types were also evaluated. In the text entry application, users were required to complete a text entry task and the mobile game application required the users to play a mobile based Battle Royale game called "PlayerUnknown's Battlegrounds (PUBG) Mobile<sup>1</sup>". PUBG was selected based on its popularity

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<sup>1</sup><https://www.pubg.com/>

(400 million players), level of engagement and demographics (people aged between 15-35 years who may be prone to long working and gaming sessions). In both applications, the users were required to complete all three modalities:

- **Modality 1:** Visual alert feedback and self-correction
- **Modality 2:** Audio alert feedback and self-correction
- **Modality 3:** EMS feedback and automatic correction

In each application, participants were required to complete all three modalities in a counterbalanced order to minimize learning effects. The independent variables in the study were the three different modalities and the dependent variables were the average correction response times, and user perception parameters such as overall experience, accuracy of correction feedback, engagement and task disruption, and comfort. Each study session lasted approximately 75 minutes and the participants were compensated \$15 for their participation. This study was approved by the Institutional Review Board of the University of Central Florida.

### *3.3.5 Research Hypotheses*

Our study was designed to determine the effects of automatic or self-posture correction on user experience across the two applications, and three modalities. As such, we expect significant differences across the three modalities which could influence user experience. For investigating into the user perception, we have five research hypotheses with two parts namely, (a) in text entry, and (b) in mobile game.

- **H1:** In the text entry (a) or the mobile game (b), the average correction response time to slouching feedback will be faster in EMS feedback compared to the visual and audio alert feedback.
- **H2:** In the text entry (a) or the mobile game (b), the user perception of accuracy of slouching posture correction in EMS feedback will be greater than visual and audio alert feedback.
- **H3:** In the text entry (a) or the mobile game (b), comfort in EMS feedback will not be significantly different compared to visual and audio alert feedback.
- **H4:** In the text entry (a) or the mobile game (b), no evidence will be found for a difference in task disruption across the visual, audio, and EMS feedback
- **H5:** In the text entry (a) or the mobile game (b), automatic correction using EMS feedback delivers better user experience compared to visual and audio alert feedback.

### 3.3.6 *COVID-19 Considerations*

Due to the ongoing COVID-19 pandemic, we wanted to ensure safety for the participants and researchers. Following our institutions guidelines, all individuals were required to always wear face masks. Between each participant, we sanitized all devices and surfaces that the participants and researchers would be in contact with, to ensure safety during the study. Furthermore, all users were required to wear a face mask to participate in the study. We also provided hand sanitizer, cleaning wipes, and latex gloves to reduce risk of contracting the disease. Though we cleaned all surfaces between participants, we allowed participants to clean devices as desired.



### 3.3.7 *Experimental Procedures*

Prior to starting the experiment, participants reviewed the consent form that details the experiment, safety, risks, compensation, and compliance, and were required to provide verbal consent for the study session to start. Participants then completed a survey on their knowledge and experience on workplace related posture issues, intervention technology and EMS. Next, IMU sensors were placed on the participants on their deltoids and center of the collar bone above the chest (as shown in Figure 3.3) for detecting slouched posture and data collection. Adhesive EMS electrodes were placed on the rhomboid muscles prior to the EMS feedback session for correcting slouching (as shown in Figure 3.4). Subsequently, IMU sensors were corrected for offset, and calibrated with participants seated in upright and slouched positions and with their hands placed on the keyboard or holding the smartphone. During calibration, participants emulated slouched positions by inclining their torso and rolling their shoulders forward. These upright and slouched posture angles were recorded.

Before the EMS feedback session, an EMS intensity calibration process was done manually for each participant, and moderators incremented the intensity until an involuntary muscular contraction causing posture correction is affected. The participants were calibrated manually only once for EMS intensity to generate a physiological response of sitting upright. During calibration, participants were asked to slouch, and moderators manually incremented the EMS intensity. As EMS also produces a tactile or haptic effect even at low intensities, participants were asked to not respond to the tactile or haptic effect to ensure the haptic/tactile component of EMS does not contribute to the automatic correction process in any way. Moderators additionally asked participants to verbally respond specifically to the following questions during calibration to ensure rhomboid muscular contraction and participant comfort: 1) when they initially felt the stimulation (haptic sensation), 2) when the intensity was generating an involuntary muscular contraction and/or when they are

experiencing the pulling force towards the upright posture, 3) when any pain is experienced. For each participant, when involuntary muscular contraction was confirmed verbally by the participant and visually verified by the moderators, the optimal EMS intensity that was generating an involuntary muscular contraction to correct the slouched posture, was recorded, and selected for the EMS part of the study.

The above steps are similar for both the text entry and the mobile gaming applications. In the text entry task, participants were asked to read from a PDF document and type into a word document. The PDF and word documents were presented in a 50-50 split screen. For the purpose of conducting the study, the PDF zoom was set to 40% to promote or cause slouching while reading (illustrated in Figure 3.8). In the mobile game task, participants were asked to play PUBG mobile (illustrated in Figure 3.9). In both applications, the user's posture was monitored for slouching. The study comprised of three parts: visual, audio, and EMS feedback. Each part of the study is 15 minutes in duration and all participants were required to finish all three parts to complete the study. Participants completed a survey about their experience after each part and a comparative survey on their overall experience at the end of the study. All data from sensors and EMS were recorded for analysis and reporting.

#### *3.3.7.1 Visual feedback and self-correction*

- ***Text Entry Application:*** When slouching was detected by the system based on the IMU sensor feedback, a Windows 10 visual popup notification "Please correct your posture" is displayed on the bottom right corner of the monitor (illustrated in Figure 3.10a) and the users were required to sit upright and self-correct their slouched posture till a second visual popup notification "Posture corrected" is displayed to the user (illustrated in Figure 3.10b). The response times for correcting the slouched posture were recorded.

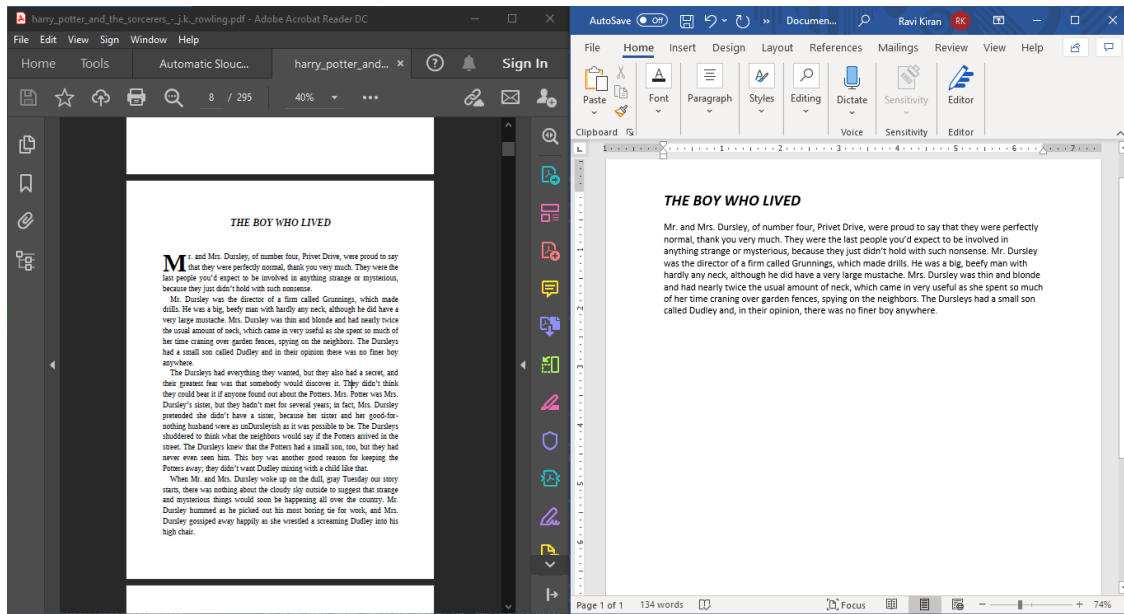


Figure 3.8: Text entry study showing 50-50 split screen with a PDF document (zoom set to 40%) on the left and a Microsoft Word document (zoom set to page width) on the right. Participants were required to read from the PDF document and type in to the Word document.



Figure 3.9: Mobile game study showing lobby area of PUBG mobile prior to start of the game.

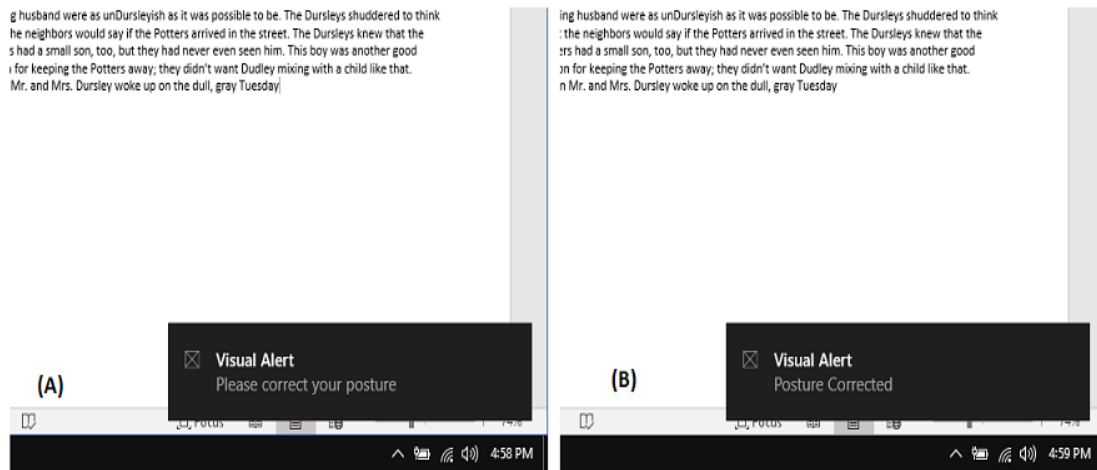


Figure 3.10: Text entry study-visual feedback: showing Windows 10 pop-up visual notification on the bottom right of the screen. (A) To correct posture when slouching is detected. (B) After posture has been corrected.



Figure 3.11: Mobile game study-visual feedback: showing visual notification badges drop down from the top of the display. (A) To correct posture when slouching is detected. (B) After posture has been corrected.

- **Mobile Game Application:** When slouching was detected by the system based on the IMU sensor feedback, an SMS is sent from the C# application to the smart phone with the message

"Posture alert: Please correct your posture" and is displayed as a drop down badge notification on the smartphone (illustrated in Figure 3.11a). After receiving the visual alert notification, the users were required to sit upright, and self-correct their slouched posture till another SMS containing the message "Posture corrected" is displayed to the user (illustrated in Figure 3.11b). The response times for correcting the slouched posture were recorded.

#### 3.3.7.2 *Audio feedback and self-correction*

- ***Text Entry Application:*** When slouching was detected by the system, an audio notification "Please correct your posture" is activated and the users were required to sit upright, and self-correct their slouched posture till an another audio notification "Posture corrected" is presented to the user. The response times for correcting the slouched posture were recorded.
- ***Mobile Game Application:*** When slouching was detected by the system, an audio notification bell sound is activated and the users were required to sit upright, and self-correct their slouched posture till another audio notification bell is activated for the user. The response times for correcting the slouched posture were recorded.

#### 3.3.7.3 *EMS feedback and auto-correction*

- ***Text Entry and Mobile Game Applications:*** When slouching was detected by the system, the EMS is activated to apply the recorded EMS intensity to the rhomboid muscles to invoke an involuntary muscle contraction. This muscle contraction produces a pulling force in the opposite direction to the slouched posture and to generate the physiological response of sitting upright by correcting the torso inclination and shoulder roll caused by slouching. Figure 4.1(A) and (C) illustrate the slouched posture during the mobile game and the text entry studies respectively. Figure 4.1(B) and (D) illustrate the corrected posture after EMS has been

applied in the mobile game and the text entry studies respectively. The EMS is deactivated once the upright position is detected. The response times for correcting the slouched posture were recorded.

### 3.4 Results

The average number of slouches in the text entry condition was (7.72, 10, and 8.72) for the audio, visual and EMS feedback modalities respectively and (7.05, 9.11, and 8.38) for the audio, visual and EMS feedback modalities, respectively in the mobile game condition. The average torso inclination and shoulder roll angles were recorded for slouched posture during the calibration process and utilized for detection of slouching which are illustrated in Table 3.2. For text entry, mean torso inclination angle was  $21^{\circ}$  ( $S.D = 3.88^{\circ}$ ), while the mean shoulder roll angle was  $15.1^{\circ}$  ( $S.D = 3^{\circ}$ ). For the mobile game, the mean torso inclination angle was  $18.24^{\circ}$  ( $S.D = 2.8^{\circ}$ ), while the mean shoulder roll angle was  $13.84^{\circ}$  ( $S.D = 2.22^{\circ}$ ). For the text entry application, the mean electrical stimulation intensity required to correct slouched posture was  $39.72\text{ mA}$  ( $S.D = 13.17\text{ mA}$ ) while for the mobile game task, the mean electrical stimulation was  $47.22\text{ mA}$  ( $S.D = 11.08\text{ mA}$ ).

To address H1, a one-way repeated measures ANOVA was performed on the influence of correction feedback type on the average correction response times taken for correcting detected slouched postures after correction feedback is presented to the user in the text entry and the mobile game tasks separately. To address H2 through H5, non-parametric Friedman tests of differences among repeated measures were conducted on the users' ranking of effectiveness of correction feedback, comfort, task disruption and overall experience. Wilcoxon signed rank tests were performed if significant differences were found. The results were consolidated and presented in Table 3.3.

For H1(a), all effects were statistically significant at the .05 significance level. The main effect for

Table 3.2: Average Slouching Angles (degrees).

Slouch Angle	Application	Mean	S.D
Torso Inclination Angle	Text Entry	21.00°	3.88°
	Mobile game	18.24°	2.80°
Shoulder Roll Angle	Text Entry	15.10°	3.00°
	Mobile game	13.84°	2.22°

the correction feedback type yielded  $F(2, 34) = 5.382, p < .05$ , indicating a significant difference between visual feedback ( $M = 3.86, S.D = 1.27$ ), audio feedback ( $M = 3.9, S.D = 1.28$ ) and EMS feedback ( $M = 2.89, S.D = 1.74$ ). The average correction response times were faster for EMS feedback than the visual feedback ( $t_{17} = -0.961, p < 0.05$ ), but no significant differences were found between EMS and audio feedback types, and between visual and audio feedback types. For H1(b), all effects were statistically significant at the .05 significance level. The main effect for the correction feedback type yielded  $F(2, 34) = 20.66, p < .001$ , indicating a significant difference between visual feedback ( $M = 5.98, S.D = 2.4$ ), audio feedback ( $M = 4.44, S.D = 0.75$ ) and EMS feedback ( $M = 2.70, S.D = 1.04$ ). The average correction response times were faster for audio feedback than the visual feedback ( $t_{17} = -1.538, p < 0.05$ ), the EMS feedback was faster than Visual feedback ( $t_{17} = -3.276, p < 0.01$ ), and also faster than the audio feedback ( $t_{17} = -1.737, p < 0.001$ ). The post-hoc analysis between the three feedback types shows that the hypothesis H1(a) tested false in that the average correction response times were faster in the EMS feedback type compared to the visual feedback but not the audio feedback. In the case of H1(b), the hypothesis tested true, in that the average correction response times were faster in the EMS feedback type compared to the visual, and audio feedback types as illustrated in Figure 3.12 (A) and (B).

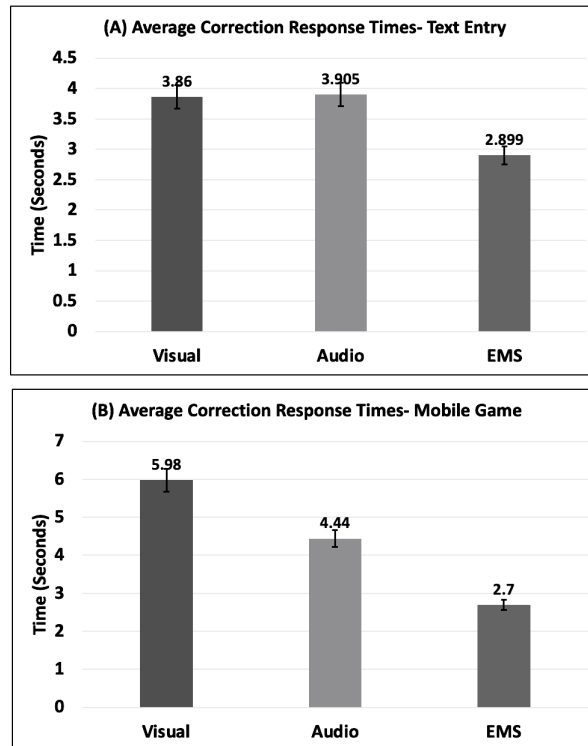


Figure 3.12: Average Correction Response Times (in Seconds) across (A) Text Entry and (B) Mobile Game for all correction feedback types - (1) Visual, (2) Audio, (3) EMS. Error Bars: 95% CI.

Table 3.3: Friedman test results on the user ranking for H2-H5.

User perception	Application	$\chi^2$	$p$
Accuracy of Correction Feedback	Text Entry	3.592	0.166
	Mobile game	7.259	0.027*
Comfort	Text Entry	1.345	0.510
	Mobile game	4.550	0.103
Task Disruption	Text Entry	0.092	0.955
	Mobile game	5.607	0.061
Overall Experience	Text Entry	0.407	0.816
	Mobile game	0.400	0.819

Note: \* indicates significant difference  $P < 0.05$ .



For H2(a) and (b), the test rendered  $\chi^2 = 3.591, p = 0.166$  which was insignificant ( $p > .05$ ) for the text entry application, while for the mobile game application, the test rendered ( $\chi^2 = 7.259, p = 0.027$ ) which was significant ( $p < .05$ ). A post-hoc analysis with Wilcoxon signed-rank tests was conducted for the mobile game application with a Bonferroni correction applied, resulting in a significance level set at  $p < 0.017$ . Median perceived accuracy of slouching correction for the Visual, Audio, EMS feedback were 6,6,7 respectively. There was a statistically significant difference between the visual and the EMS correction feedback type ( $Z = -2.591, p = 0.010$ ), and also between EMS and audio correction feedback type ( $Z = -2.585, p = 0.010$ ). However, there was no significant difference between audio and visual correction feedback types ( $Z = -0.942, p = 0.346$ ). Therefore, H2(a) tested false and indicated that the users perceived all three feedback types equally accurate in the text entry application. Whereas H2(b) tested true and indicated that the users perceived that the accuracy of EMS correction feedback was more effective than the visual and the audio feedback in the mobile game application.

For H3(a) and (b), the test rendered  $\chi^2 = 1.345$  and  $p = 0.510$  which was insignificant ( $p > .05$ ) for the text entry application, while for the mobile game application, the test rendered  $\chi^2 = 4.550$  and  $p = 0.103$  which was insignificant ( $p > .05$ ). Therefore, both H3(a) and (b) tested true and indicated that users perceived all three feedback types equally comfortable in the text entry and the mobile game application. For H4(a) and (b), the test rendered  $\chi^2 = 0.092$  and  $p = 0.955$  which was insignificant ( $p > .05$ ) for the text entry application, while for the mobile game application, the test rendered  $\chi^2 = 5.607$  and  $p = 0.061$  which was insignificant ( $p > .05$ ). Therefore, both H4(a) and (b) tested true and indicated that users perceived EMS correction feedback's disruption no worse than the other two feedback types in the text entry and the mobile game application. For H5(a) and (b), the test rendered  $\chi^2 = 0.407$  and  $p = 0.816$  which was insignificant ( $p > .05$ ) for the text entry application, while for the mobile game application, the test rendered  $\chi^2 = 0.400$  and  $p = 0.819$  which was insignificant ( $p > .05$ ). Therefore, both H5(a) and (b) tested false and indicated that

users perceived overall experience across all feedback types equally well in the text entry and the mobile game application.

Participants ranked their shared responsibility with auto-correction utilizing EMS on a 7-point scale where 1 means not at all and 7 means completely. The mean shared responsibility exhibited by the users was 2.77 ( $S.D = 1.7$ ) in the text entry task, while for the mobile game condition, users reported that they helped/aided auto-correction with a mean shared responsibility of 2.5 ( $S.D = 0.95$ ). Participants also ranked how interesting the EMS concept was to use for posture correction on a 7-point scale where 1 means not at all and 7 means completely. The mean ranking received for EMS concept being interesting was 6.58 ( $S.D = 1.01$ ). 27 out of 36 users reported that they would purchase EMS feedback for slouched posture correction if it were commercially available. Participants' responses when asked to comment on their experience with EMS showed that EMS feedback felt *"more natural"*, *"not easily ignorable"* and better than audio and visual modalities as they cause *"over/under correction"* of posture. Additionally, participants also reported about the EMS feedback that *"the system accurately initiated the stimulus when slouched and stopped after posture was corrected."* and that EMS *"would enable me to not worry about my posture during highly engaging tasks."* One user responded that EMS is *"unobtrusive and discrete method of auto-correcting posture."* and EMS was the *"least disruptive"*. Further, users reported *"I cannot listen to some one while i am trying to read and type."*, and *"the visual notifications were annoying and distracting when i was typing."* indicating that the audio and visual feedback were placing a cognitive load on the user. Other user comments include *"this can be a good training device but EMS requires getting used to"*, *"it actively and immediately corrected my slouched posture"*, *"training device for maintaining proper posture"*, *"the tingling sensation feels weird but good"*, *"this can seriously help people with posture problems."*

### 3.5 Discussion

While slouching detection and alert systems were designed and tested, we note that posture correction response times and user perception of the systems have not been measured or reported. Therefore, our study focused on evaluating the performance, and user perception of our autonomous system for detecting and correcting slouching. Our automatic slouching correction using the EMS feedback system outperformed the visual and audio feedback types based on the average correction response times suggesting that visual and audio feedback place an additional cognitive load on the user while being engaged in their task and rely completely on the user's willingness to self-correct their posture. However, as EMS feedback does not require the user's attention, this has made it significantly faster than the other two feedback types.

Users also perceived that EMS feedback corrected their posture more accurately than the other two feedback types that required self-correction. Users reported that self-correction in the visual and the audio feedback types caused them to always over-correct their posture as their awareness of it was minimal while being engaged in the task at hand. Whereas EMS feedback did not require the user's attention and always accurately activated when the slouched posture was detected and deactivated after a posture had been corrected. The user rankings on accuracy of EMS feedback indicated that EMS feedback was perceived to be more accurate in the mobile game application than the text entry application. This interesting finding may have been due to different factors such as nature of the two applications, complexity of the task, users' connection to the device and varied range of motion involved in auto-correction using EMS feedback across the two applications. It was also interesting to note that EMS feedback and auto-correction were perceived equally comfortable and no more disruptive than traditional visual and audio alert feedback but with the added advantage of automatic correction. This may have been because EMS feedback relied entirely on the user's physiology and careful EMS intensity calibration with user feedback on their level of comfort to

deliver a somatosensory feedback that discretely enabled posture awareness without disruption. With regards to comfort, users reported that their awareness of the IMUs and EMS electrodes on their body was minimal suggesting that our prototype could be a viable wearable intervention device for posture correction.

Further, shared responsibility in aiding the auto-correction using EMS was exhibited and reported by the users suggesting that the sensory confirmation delivered by activation and deactivation of EMS encouraged their involvement in the posture correction process and increased their posture awareness. This demonstrated that users can adapt to the system and gradually utilize it as a training device for development of good postural habits in the long run. The EMS intensity required for auto-correction in the mobile game task was higher than the text entry task, suggesting that the task type, level of engagement, range of motions involved in the correction process influence the EMS intensity required for correcting different levels of slouching. As shown in the results section, the EMS intensity varied across the study population. This could be due to factors such as different body types, muscle physiology, and activity levels.

Finally, users perceived that EMS was an interesting concept to use for automatic posture correction while they were engaged in their tasks. 20 out of 36 users reported that EMS feedback and auto-correction was their most preferred feedback type while 75% of the study population was willing to purchase the automatic correction using EMS feedback if it were a commercially available product. Therefore, our autonomous system could be a valuable alternative or an addition to existing environment, health, and safety (EHS) protocols at workplaces for enhancing productivity, worker health and in preventive health care.

In conclusion, we have demonstrated that our physiological feedback loop based on automatic slouching detection and correction with EMS is a viable approach to supporting posture correction. Our auto-correction system utilizing EMS feedback demonstrated significantly faster posture

correction response times compared to the self-correction in the visual and audio feedback. Our approach also showed that users perceived EMS feedback to be more accurate, just as comfortable and produced no more disruption than the alternative techniques it was tested against in both the text entry and the mobile game applications. Therefore, automatic slouching detection and correction utilizing EMS shows promising results and can be developed as an alternative method for posture correction. Our approach could prove useful in preventive healthcare to avoid workplace related RSI and be particularly beneficial to people involved in highly engaging tasks such as gaming, diagnostic monitoring, and defense control tasks.

The next chapter presents the design and development of an automatic AWD detection and correction utilizing EMS and human subject study conducted to evaluate the effectiveness of our automatic approach.

## CHAPTER 4: AUTOMATIC DETECTION AND CORRECTION OF ASYMMETRIC WEIGHT DISTRIBUTION (AWD)

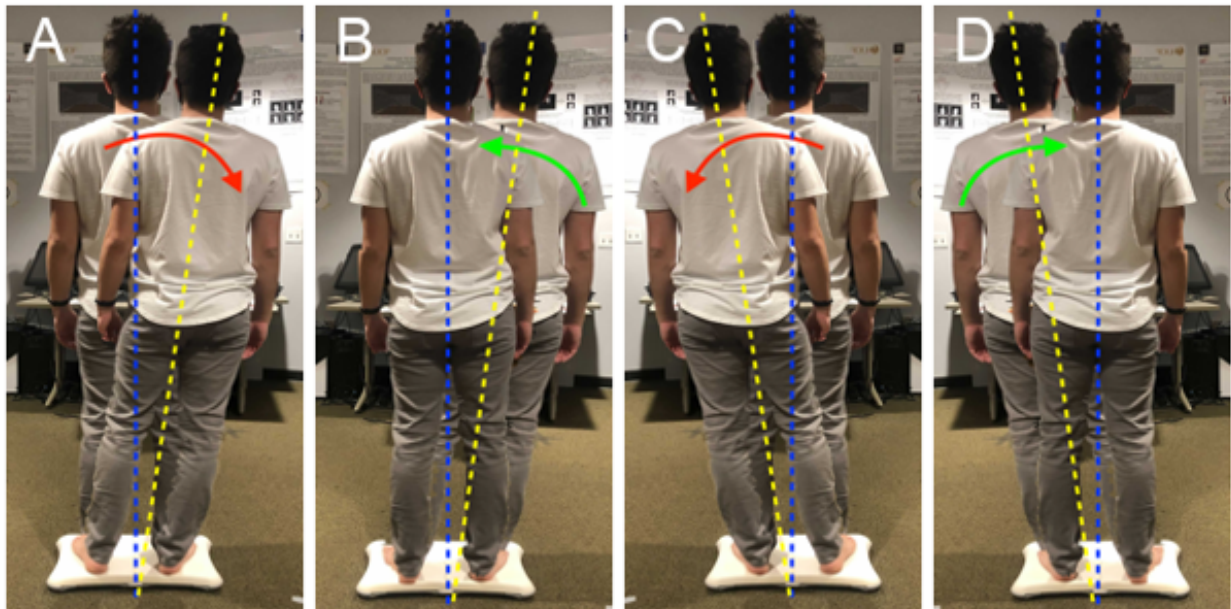


Figure 4.1: Impaired balance can have long-term health ramifications. Presented here are images of asymmetric weight distribution (AWD) due to prolonged standing and restored balance conditions using electrical muscle stimulation (EMS): (A) AWD right, (C) AWD left, (B) & (D) EMS feedback based stabilization and restoration of balanced posture. The red arrows indicate direction of progressive AWD and green arrows indicate a counter-weight shift balance stabilization due to EMS feedback correction to the tibialis muscle.

Asymmetric weight distribution is another very common static moderate activity poor posture affecting people especially from the working population. From the literature, the existing intervention technology only offers postural sway detection and alerts, and requires the users' willingness and effort to self-correct their AWD posture. Additionally, EMS demonstrated its capability to correct slouched posture through involuntary muscular contractions. This has presented an opportunity to extend the automatic posture correction capabilities of EMS based feedback for the design and

development of a wearable intervention technology with automatic AWD detection and subsequent AWD correction to restore balanced posture.

For automatic detection and correction of AWD, we developed an intervention prototype based on a physiological feedback loop that relied on load sensors and EMS (illustrated in Fig 4.2). Our prototype employed a wireless Wii Balance Board (WBB) for measuring changes in weight distribution across the two legs using the balance ratio of the weights displaced by the two legs separately, and the *openEMSstim* package [121] for presenting the EMS correction feedback. A C#-based user interface using a Wii-mote library was developed to integrate the WBB with the EMS hardware to complete the physiological feedback loop. AWD is mainly characterized by progressive and/or unusual leaning to either side [90], our system was designed to detect these changes in weight distribution across the two legs using the shift in balance ratio representing the AWD conditions.

#### **4.1 Time and Balance Thresholds**

Asymmetrical leg loading can be detected from the shift in balance ratio calculated from the weight displacement information obtained from the load sensors in the WBB. Our proposed system detected AWD when the user's balance ratio approached and crossed preset balance ratio and time thresholds. To improve our system robustness and tune our system for optimal performance, we collected ecologically valid balance ratio data from 10 participants performing 10 typical actions one performs consciously or unconsciously when they are standing idly (illustrated in Figure 4.3). These 10 unique actions were identified based on general movement observations of employees taking breaks from standing. These actions were interleaved with moderate and extreme leaning actions to ensure AWD conditions were embedded in each session. The balance ratio patterns of the 10 actions are shown in Figure 4.4. A grid search was then employed to find the balance ratio

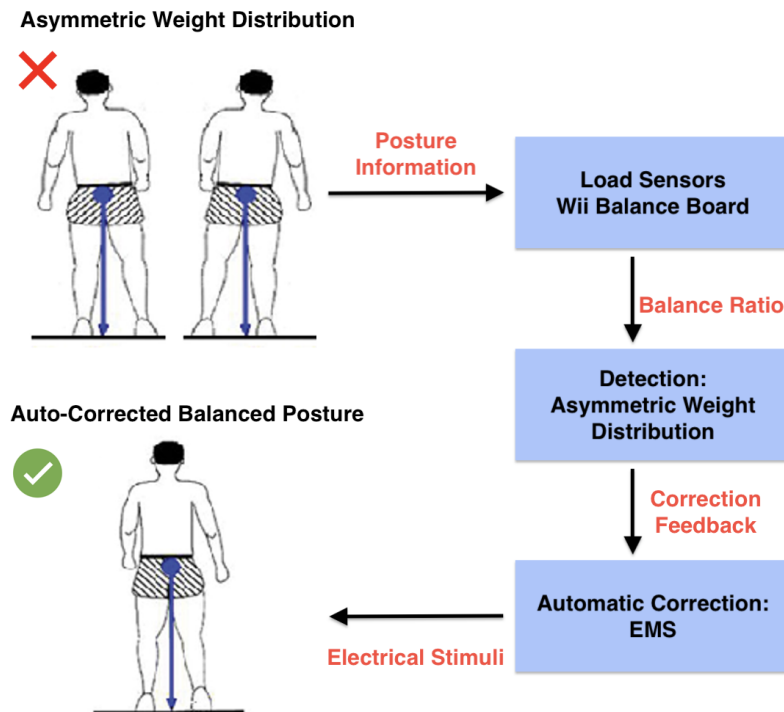


Figure 4.2: Physiological feedback loop: Automatic asymmetric weight distribution detection and correction system. Asymmetric weight distribution posture (top) illustrates leaning to either side and the auto-corrected posture (bottom) illustrates the restored balanced posture achieved through a counter-weight shift strategy using EMS.

and time thresholds that optimized the accuracy of AWD detection. Since our primary concern was the impact of false positives on user perception and to prevent unwarranted correction feedback, we selected thresholds that minimized false positives first, maximized true positives second, and maximized the per-frame Jaccard index of similarity [168] with the manually marked per-frame ground truth third. With valid data collected from 10 participants, using a leave-one-subject-out protocol, we found that at a time threshold of 2.9 seconds and balance ratio threshold of 1.25, our system achieved high accuracy of 96% for true positive AWD detection, 0.1% for false-positive AWD detection, and 0.3% for false rate. The balance ratio of 1.25 translates to a left-to-right or right-to-left AWD balance ratio of 55.5 : 44.5.



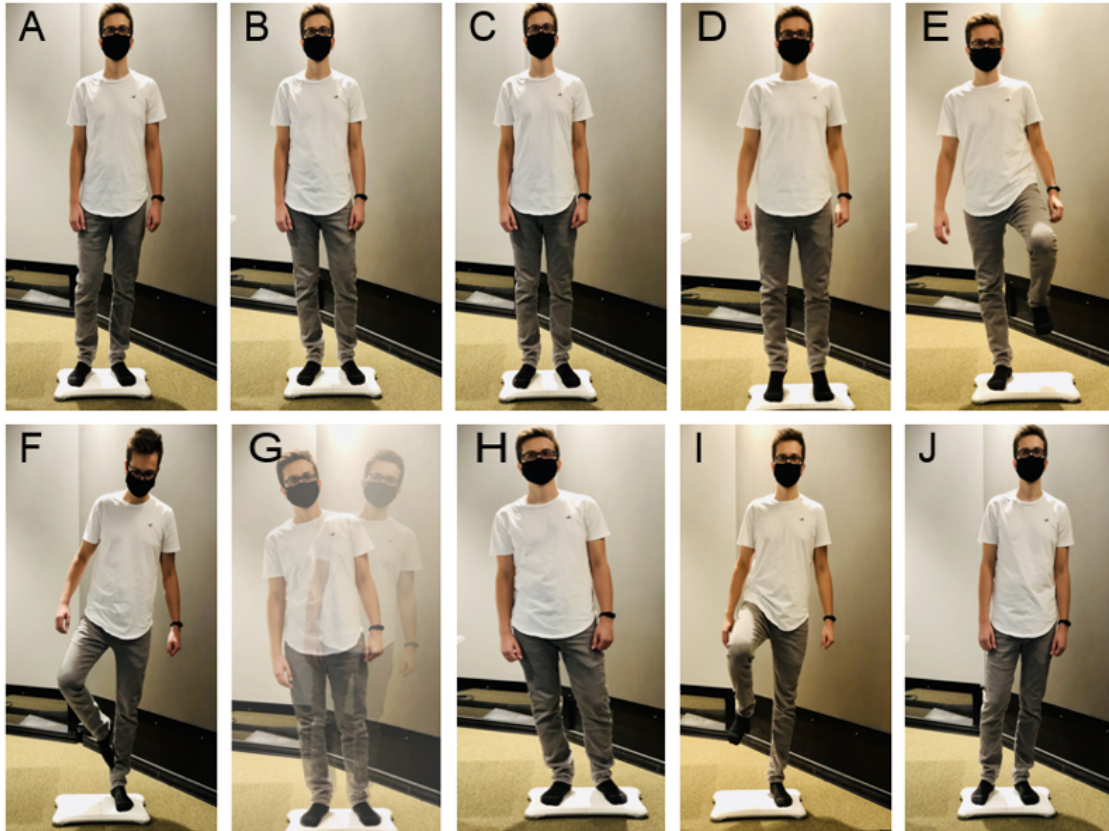


Figure 4.3: Some examples of typical actions performed during standing activities based on movement observations of employees taking breaks after standing. (A) Lean slight left, (B) Lean slight right, (C) Balanced, (D) Calf raise and reset, (E) Lift left leg and reset, (F) Scratch leg and reset, (G) Sway and reset, (H) Lean extreme right, (I) Lift right leg and reset, (J) Lean extreme left.

The preset time and balance ratio thresholds obtained through our tuning process allowed the AWD detection system to overcome measurement errors, mitigate false positives, and ensured that typical movements such as actions illustrated in Figure 4.3 did not lead to false-positive AWD detection or activate unwarranted correction feedback. When the user's balance ratio approached and crossed the preset balance ratio threshold of 1.25, a countdown timer set to the preset time threshold value of 2.9 seconds was initiated to provide correction feedback after the time threshold had elapsed. The purpose of the timer is to ensure that false positives due to participant behavior do not trigger a correction feedback response.

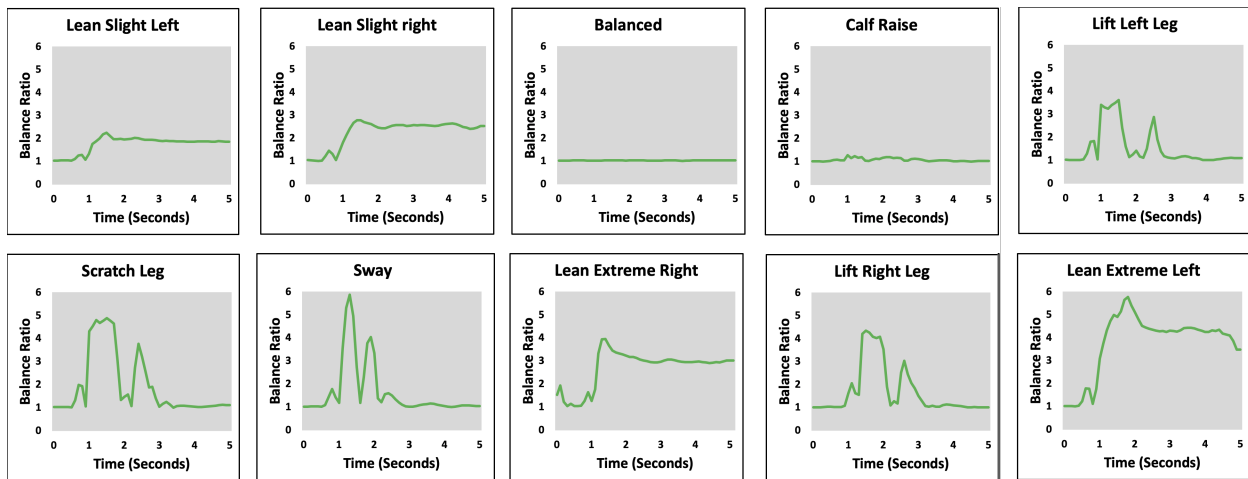


Figure 4.4: Balance ratio patterns of the 10 actions performed by users (illustrated in Figure 4.3) for the tuning process to determine balance and time thresholds for AWD detection. The lean actions representative of AWD exhibited higher balance ratios and for prolonged time durations in comparison to the other actions.

## 4.2 Correction Feedback

When AWD is detected, automatic correction feedback would be presented to the user by applying electrical stimulus to the tibialis muscles for generating a counter-weight shift force in the opposite leg to the direction of the AWD leaning and thereby, generating a physiological response to stabilize the user back to a 50:50 balanced weight distribution position. A pair of electrodes on each leg (illustrated in Fig 4.8b) would be utilized for contraction of the tibialis muscle which causes the foot to roll outward, thus generating a physiological response of a counter-weight shift. This generated counter-weight shift attempts to redistribute the weight more evenly across the two legs, thereby stabilizing the user back to the balanced 50:50 weight distribution position. Calibration of the WBB and EMS intensity play a crucial role in the effectiveness of the system. The calibration process includes correcting offset values of the load sensors in the WBB prior to start of the study session. The users' balance ratio in balanced position and emulated AWD leaning positions relative

to the balanced position are monitored to ensure WBB is calibrated. For the EMS calibration, the EMS intensity would be manually incremented to deliver an intensity that is optimal for generating involuntary muscular contraction, comfortable, and avoid any discomfort or pain to the user. This EMS intensity, provided to the user for generating the necessary force for correcting AWD posture and restoring the balanced position, would be recorded and utilized during the experiment. The Trans-cutaneous electrical stimulation (*TENS*) device can deliver intensities between (0-70 *mA*). A continuous square wave at a pulse width of 100  $\mu$ s with a frequency of 75 *Hz* at the recorded EMS intensity would be presented as EMS feedback to the users. The EMS calibration procedure is described in detail in section 4.4.5.

### 4.3 Operation

Our Physiological feedback loop for detecting and correcting AWD relied on the changes in balance ratio along with the total weight distributed on each leg. This allowed our system to detect AWD left/right conditions when the balance and time thresholds have been crossed. AWD occurs when a user unevenly distributed body weight across the two legs. This places an additional stress on the ankle, knee, hip, and lower back. To detect these AWD conditions, our system utilized the balance and time thresholds determined in Section 4.1. Figure 4.5 illustrates the activation and deactivation of EMS correction feedback when an AWD left condition was detected and corrected for a participant during the study. Initially, under a balanced posture condition, the EMS left leg and EMS right leg remain deactivated. A timer with preset time threshold of 2.9 *Seconds* was activated when the user's balance ratio gradually increased and crossed the preset threshold of 1.2. Upon completion of the timer, if the balance ratio still remained above the threshold, the EMS was activated to apply a stimulus of 50 *mA* to invoke a muscular contraction on the right tibialis muscle (EMS Right Leg) for generating a counter weight shift and restore balanced posture. The EMS was

deactivated immediately after the balanced posture is restored. A correction response time of 1.2 *Seconds* was recorded between activation and deactivation of the EMS Right Leg. The AWD right condition is similarly detected and corrected by activating and deactivating EMS Left Leg.

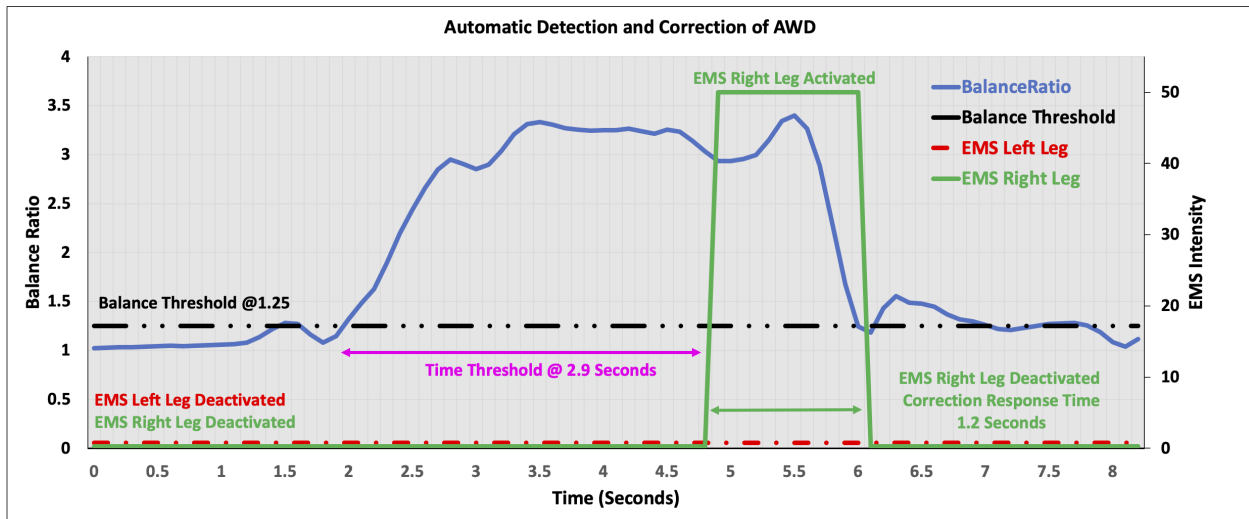


Figure 4.5: Automatic Detection and correction of AWD: Graph showing EMS activation and deactivation. When the user’s balance ratio approached and crossed preset balance ratio and time thresholds, EMS was activated for AWD correction. EMS was deactivated when 50:50 balance was restored.

#### 4.4 Methods

The goal of this study was to evaluate the overall effectiveness and user perception of our automatic AWD detection and correction feedback system using EMS compared to traditional audio and vibro-tactile feedback modalities. The audio and vibro-tactile feedback modalities required self-correction by the user based on audio and vibro-tactile notifications delivered to them, respectively. We also identified two common use cases of everyday activities with varying levels of engagement and posture awareness such as quiet standing and playing a mobile game to investigate the effect of cognitive demand on posture awareness, AWD occurrence, and type of correction feedback.

Our objective was to determine if our automatic AWD detection and correction system using EMS feedback would be a viable technique for correcting AWD as opposed to the audio and the vibro-tactile feedback types while standing idly or being engaged in cognitively demanding task.

#### 4.4.1 Subjects and Apparatus

We recruited 36 users (*Male* = 29, *Female* = 7) for the study with 18 users for each application-quiet standing, and mobile game. All users were aged 18 years and above with mean age of 24.67 years (*S.D.* = 3.98 years), mean weight of 71.1 Kg (*S.D.* = 10.88 Kg), and mean height of 167.3 cm (*S.D.* = 8.94 cm). All users were able-bodied and had corrective 20/20 vision. For monitoring the balance ratio along the medial lateral axis, a Wii balance board was utilized. A Grove-vibration motor with double-sided disposable adhesives was utilized for delivering the vibro-tactile feedback (illustrated in Fig 4.8a). An off-the-shelf TENS unit (*TN SM MF2*), and *openEMSStim* package [120] was utilized for generating the EMS feedback and controlling the activation and modulation of the intensity of the electrical stimuli supplied to the muscles, respectively. A 14" Intel *i7* laptop was utilized for the study user interface and an iPhone *SE 2nd* generation was employed for the mobile game application. Qualitative data from the pre-questionnaire survey on participants' prior exposure to balance alert devices and EMS, experience with posture problems, and AWD is illustrated in Table 4.1. Participants ranked their exposure and experience on a 7-point Likert scale with 1 meaning never/no experience and 7 meaning frequently/very experienced.

Table 4.1: User ranking on posture awareness, devices, and EMS. User ranking on a 7-point Likert scale. QS: Quiet standing, MG: Mobile game.

User Experience	Application	Mean	S.D
Exposure to balance alert devices	QS	1.44	0.70
	MG	2.11	1.28
Exposure to EMS	QS	2.56	1.39
	MG	1.94	1.25
Prolonged standing	QS	4.39	1.87
	MG	4.11	1.67
Experienced AWD	QS	4.33	2.01
	MG	3.67	2.08



Figure 4.6: Participants played PUBG mobile in the mobile game condition. Image shows the lobby area of the game prior to starting.

#### 4.4.2 Experimental Design

To investigate the performance and feasibility of our approach, a 2 by 3 mixed subjects experiment with 36 users was conducted. The within-subject factor was the feedback type (audio, vibro-tactile, and EMS) and the between-subject factor was the application type (Quiet standing (QS) and Mobile game (MG)). The performance of our automatic AWD correction using the EMS feedback was compared against the self-correction in the audio and vibro-tactile feedback techniques. A quantitative evaluation of the average correction response times and a qualitative evaluation of the perceived usability of our system were conducted across the three feedback and the two application types. In both applications, participants were required to stand on the WBB without shoes for three 15-minute sessions, one for each of the three modalities listed below. In the quiet standing application, participants were required to stand quietly (illustrated in Fig 4.7 (A), (B), & (C)), while participants played a mobile version of "PlayerUnknown's Battlegrounds (PUBG)"<sup>1</sup> in the mobile game application (illustrated in Fig 4.7 (D), (E), & (F)). PUBG mobile is an engaging battle royale game (illustrated in Fig 4.6) and was selected for this study due to its high engagement level and popularity amongst people aged between 15–35 years, who may be more prone to AWD due to prolonged standing hours at work or mobile gaming sessions. In both applications, users were required to complete the following three modalities:

- **Modality 1:** Audio alert feedback and self-correction
- **Modality 2:** Vibro-tactile alert feedback and self-correction
- **Modality 3:** EMS feedback and automatic correction

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<sup>1</sup><https://www.pubg.com/>

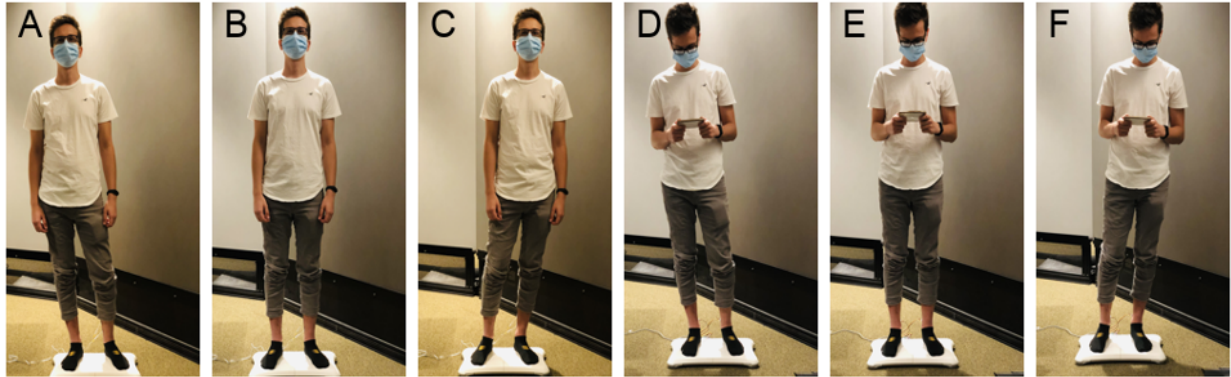


Figure 4.7: Evaluation of the effectiveness of our automatic approach across 2 different application types- Quiet Standing (A), (B), (C) and Mobile Game (D), (E), (F). Quiet Standing: (A) AWD Left, (B) Balanced, (C) AWD Right. Mobile Game: (D) AWD Left, (E) Balanced, (F) AWD Right.

In both applications, the order in which the participants were introduced to the modalities was counterbalanced to minimize learning effects. The three different modalities in the study were the independent variables and the dependent variables were the average correction response times, and user perception parameters such as accuracy of correction feedback, task disruption, comfort, and posture awareness. Each study session lasted approximately 60–75 *minutes* and the users were compensated \$15 for their participation.

#### 4.4.3 *Research Hypotheses*

Our study was designed to determine the effects of automatic or self-posture correction on user experience across the two applications, and three feedback modalities. As such, we expect to find the main and interaction effects of modality and application type on the average correction response times. We also expect to find main effects across modality or application types for user perception parameters such as correction feedback accuracy and posture awareness while no evidence of main or interaction effects is expected for comfort and task disruption. We have five research hypotheses:



- **H1:** Average correction response times to EMS feedback will be the fastest among all three modalities.
- **H2:** Correction feedback accuracy in the EMS feedback modality will be greater in comparison to the other modalities.
- **H3:** EMS feedback modality will be equally comfortable as the alternative traditional feedback types and across both application types.
- **H4:** No evidence will be found for a difference in task disruption across the three modalities.

#### *4.4.4 COVID-19 Considerations*

Due to the ongoing COVID-19 pandemic, we wanted to ensure safety for the users and researchers. Following our institution's guidelines, all individuals were required to always wear face masks. Between each user, we sanitized all devices and surfaces that the participants and researchers would be in contact with, to ensure safety during the study. Furthermore, all users were required to wear a face mask to participate in the study. We also provided hand sanitizer, cleaning wipes, and latex gloves to reduce the risk of contracting the disease. Though we cleaned all surfaces between users, we allowed users to clean devices as desired.

#### *4.4.5 Experimental Procedures*

Before the start of the study session, participants were required to review the consent document and provide their consent for participating in the research. Participants then completed a pre-questionnaire survey on knowledge and experience with balance-related intervention technology, AWD, and EMS. Upon completion of the pre-questionnaire survey, participants were required to

complete a validation study where they performed a set of the 10 typical actions on the WBB as illustrated in the Figure 4.3 to ensure the AWD detection system with the preset balance threshold (1.25) and time threshold (2.9 *seconds*) (obtained from the optimization process described in section 3.1) was able to detect the AWD conditions (Lean slight right/left, Lean extreme right/left) accurately and to mitigate the possibility of false-positive correction feedback. Next, participants were required to stand without shoes on the WBB for calibration. For the vibro-tactile alert modality, Grove vibration motors were placed on each leg with double-sided adhesives as illustrated in Figure 4.8a. Adhesive EMS electrodes were placed on each leg along the tibialis muscles before the EMS feedback session for correcting AWD as illustrated in Figure 4.8b.

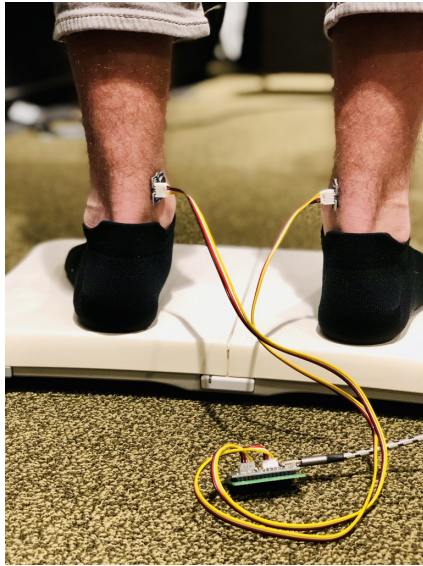
Before the EMS feedback session, users were required to stand on the WBB and were calibrated for an optimal EMS intensity that affected balance stabilization and corrected AWD posture. Each user's optimal EMS intensity level was manually calibrated by the study moderator only once. Users were asked to emulate an AWD condition of leaning left or right and the moderators incremented the EMS intensity on the opposite leg until an involuntary muscular contraction is felt by the user and generated a physiological response of a counter-weight shift in an attempt to stabilize the balance ratio. The above process was repeated for both AWD left and AWD right conditions to deliver the user with an optimal user experience in the EMS feedback session. As EMS has been known to produce a haptic effect at low intensities, users were asked to ignore the haptic effect to ensure the haptic component did not contribute to the automatic AWD correction process in any way. Additionally, during this calibration process, moderators also asked users to specifically respond verbally to the following questions to ensure tibialis muscular contraction and user comfort: 1) If and when they initially felt a haptic sensation of the EMS, 2) If and when they felt the EMS intensity generating an involuntary contraction in the leg and/or when they are experiencing the counter-weight shift force towards restoring their balance, 3) If and when they felt any pain or discomfort. For each user, this involuntary muscular contraction affecting AWD correction was

visually verified by the moderator and verbally confirmed by the user. The optimal EMS intensity which generated the counter-weight shift effect to correct AWD and was also comfortable to the user was recorded to be used for the EMS feedback session of the study (Refer Section 3.3.3 for more details on the step-by-step calibration process).

The above steps are similar in both the quiet standing and the mobile game applications. In the quiet standing application, users would be asked to stand quietly, while for the mobile game application, users would be required to play PUBG. In both applications, users would be required to stand without shoes on the WBB, and their balance ratio would be monitored for AWD (illustrated in Fig 4.7). The study comprises three parts: audio, vibro-tactile, and EMS feedback. Each part of the study is 15 *minutes* in duration and all users were required to finish all three parts to complete the study. The users were given a 5-*minute* seated break after each part of the study, where users were required to remain seated to rest their legs. Participants then completed a survey about their experience after each part. All data from WBB, correction response times, and EMS intensity were recorded for analysis and reporting.

#### *4.4.5.1 Audio feedback and self-correction:*

Upon AWD detection based on balance ratio from the WBB, an audio notification "*Leaning left/right-please correct imbalance*" is activated and the users were required to self-correct their AWD posture and stabilize their balance till another audio notification "*Stabilized*" is presented to them.



(a) Haptic motor unit placement.



(b) EMS electrode placement.

Figure 4.8: Haptic motor unit and EMS electrode placement on the tibialis muscle. (a) Vibro-tactile feedback is delivered to the legs through the haptic motor units placed on each leg. (b) EMS feedback is delivered through EMS Electrodes placed on the tibialis muscle on each leg.

#### 4.4.5.2 *Vibro-tactile feedback and self-correction:*

Upon AWD detection based on balance ratio from the WBB, a vibro-tactile notification in the form of vibration from the haptic motor is activated on the opposite leg, indicating the direction that the user was required to shift to self-correct their AWD and stabilize their balance ratio. When users' balance is stabilized the vibro-tactile notification stops, indicating a 50 : 50 balance has been achieved.

#### 4.4.5.3 EMS feedback and Auto-correction:

Upon AWD detection, the EMS feedback is activated to apply the recorded EMS intensity to the tibialis muscles in the opposite leg to the AWD lean. This invokes an involuntary muscle contraction to produce a counter-weight shift force in the opposite direction to the AWD lean for stabilizing the balance. Fig 4.1(A) and (C) illustrate the AWD left and right-leaning posture, respectively. Figures 4.1(B) and (D) illustrate the automatically corrected posture after EMS has been applied. The EMS is deactivated when the balance ratio stabilization has been achieved.

## 4.5 Results

The average number of AWD conditions observed per participant in the quiet standing application was (12.38, 13.05, and 14.11) for the audio, vibro-tactile, and EMS feedback modalities, respectively, and (12.22, 13.83, and 12.66) for the audio, vibro-tactile, and EMS feedback modalities, respectively in the mobile game application. For the quiet standing application, the mean EMS intensity required to correct AWD condition and stabilize balance posture was 50.55 mA ( $S.D = 9.05$  mA) while for the mobile game task, the mean EMS intensity was 51.94 mA ( $S.D = 8.25$  mA). To analyze the performance of our approach, we used repeated-measures 2-Factor ANOVA to determine the influence of modality and application types on each dependent variable and the consolidated results are presented in Tables 4.2, 4.3, 4.4, 4.5. For the non-parametric user perception Likert scale data, we utilized the Aligned Rank Transform (ART) tool [203] and performed repeated measures 2-Factor ANOVA tests on the aligned ranks for the user perception Likert scale data.

#### 4.5.1 Average Correction Response Times

For H1, the main effect for modality type yielded an  $F(2, 68) = 125.16$ ,  $p < 0.001$ , indicating a significant difference between Audio ( $M = 2.58$ ,  $S.D = 0.63$ ), Vibro-tactile ( $M = 1.8$ ,  $S.D = 0.45$ ), and EMS modalities ( $M = 1.32$ ,  $S.D = 0.29$ ) as illustrated in Figure 4.9a (a). The main effect for application type yielded an  $F(1, 34) = 2.744$ ,  $p > 0.05$ , indicating that the effect of application type was not significant between quiet standing ( $M = 1.8$ ,  $S.D = 0.6$ ), and mobile game ( $M = 2$ ,  $S.D = 0.79$ ) as illustrated in Figure 4.9b. The interaction effect was significant  $F(2, 68) = 5.803$ ,  $p < 0.05$ . Significant differences were found in the system performance with regards to average correction response times between different feedback modalities with EMS feedback delivering the fastest correction. As a result, we were able to accept H1.

Table 4.2: 2-Factor ANOVA: Average Correction response times (ACRT). M: Modality, A: Application.

Source	ACRT	p
M	$F(2, 68) = 125.16$	$< 0.001^*$
A	$F(1, 34) = 2.744$	0.107
M X A	$F(2, 68) = 5.803$	$0.016^*$

Note: \* indicates significant difference  $p < 0.05$ .

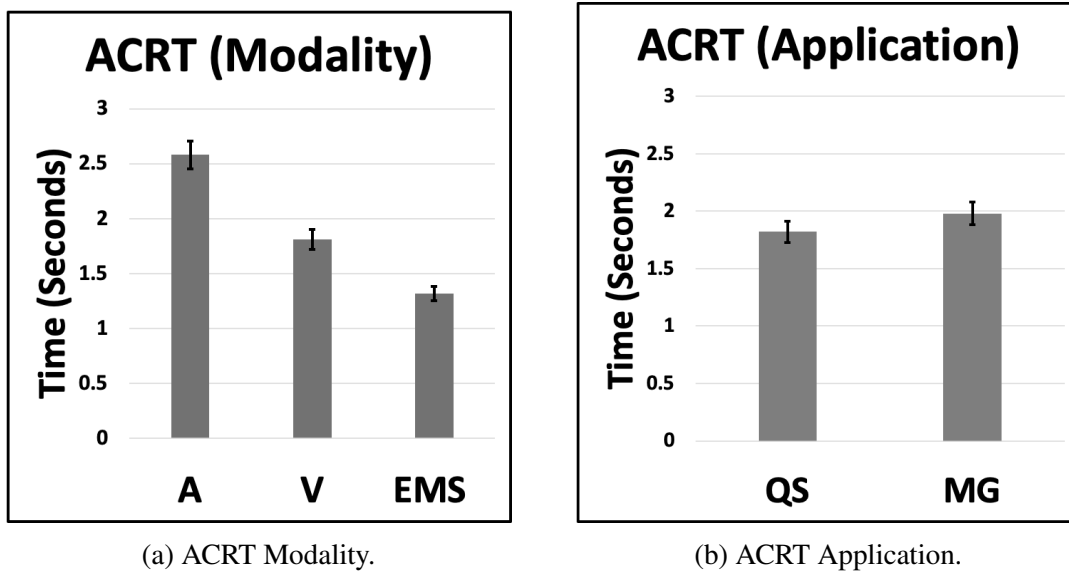


Figure 4.9: Average correction response times (ACRT) across (a) Modality, & (b) Application type. Error bars:95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game.

#### 4.5.2 User Perception of Correction Feedback Accuracy

For H2, the main effect for modality type yielded an  $F(2,68) = 4.113$ ,  $p < 0.05$ , indicating a significant difference between Audio ( $M = 5.83$ ,  $S.D = 1.03$ ), Vibro-tactile ( $M = 6.44$ ,  $S.D = 0.69$ ), and EMS modalities ( $M = 6.67$ ,  $S.D = 0.53$ ) as illustrated in Figure 4.10a. A pairwise comparison of the means showed significant differences between the audio and vibro-tactile, and audio and EMS feedback types but no evidence of significant differences between the vibro-tactile and EMS feedback. The participants perceived EMS feedback to be more accurate than the audio, but not vibro-tactile feedback and hence we were not able to accept H2. The main effect for application type yielded an  $F(1,34) = 0.052$ ,  $p > 0.05$ , indicating that the effect of application type was not significant between quiet standing ( $M = 6.3$ ,  $S.D = 0.82$ ), and mobile game ( $M = 6.33$ ,  $S.D = 0.81$ ) as illustrated in Figure 4.10b. The interaction effect was not significant  $F(2,68) = 2.988$ ,  $p > 0.05$ .

Table 4.3: 2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). M: Modality, A: Application.

Source	CFA	p
M	$F(2, 68) = 4.113$	0.021*
A	$F(1, 34) = 0.052$	0.82
M X A	$F(2, 68) = 2.988$	0.057

Note: \* indicates significant difference  $p < 0.05$ .

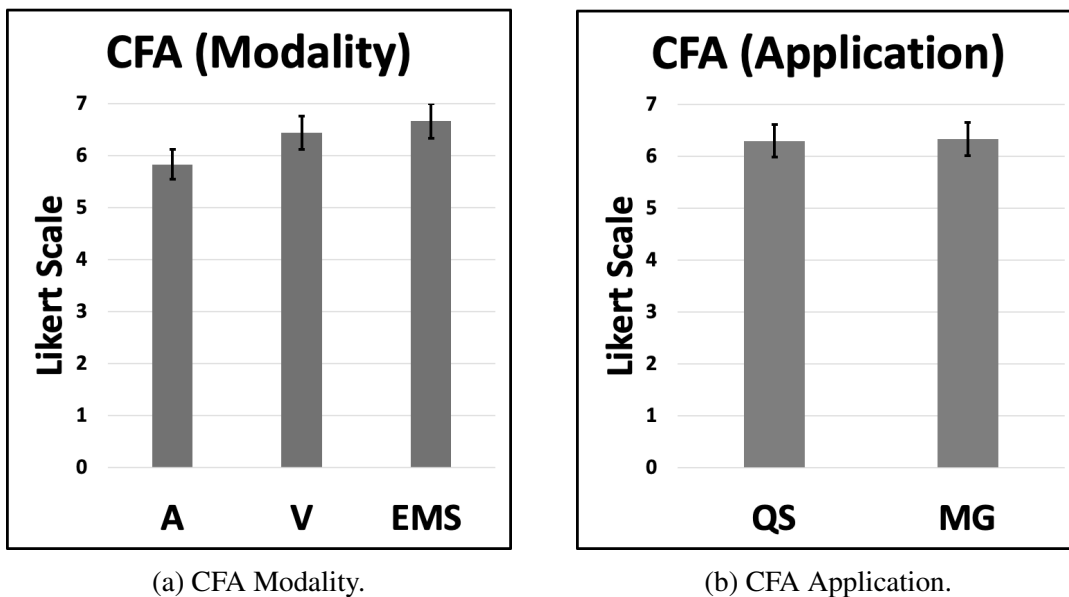


Figure 4.10: User perception of correction feedback accuracy across (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game.



### 4.5.3 User Perception of Comfort

For H3, the main effect for modality type yielded an  $F(2, 68) = 1.376, p > 0.05$ , indicating no significant difference between Audio ( $M = 6.3, S.D = 0.98$ ), Vibro-tactile ( $M = 6.36, S.D = 0.96$ ), and EMS modalities ( $M = 5.91, S.D = 1.23$ ) as illustrated in Figure 4.11a. The main effect for application type yielded an  $F(1, 34) = 1.364, p > 0.05$ , indicating that the effect of application type was not significant between quiet standing ( $M = 6.43, S.D = 1.02$ ), and mobile game ( $M = 6, S.D = 1.08$ ) as illustrated in Figure 4.11b. The interaction effect was not significant  $F(2, 68) = 2.027, p > 0.05$ . As no significant differences were found in the main effects for modality or the application type, neither modality nor application had any influence on the user comfort. As a result, we accept H3.

Table 4.4: 2-Factor ANOVA: User perception-Comfort. M: Modality, A: Application.

Source	Comfort	p
M	$F(2, 68) = 1.376$	0.259
A	$F(1, 34) = 1.364$	0.251
M X A	$F(2, 68) = 2.027$	0.14

Note: \* indicates significant difference  $p < 0.05$ .

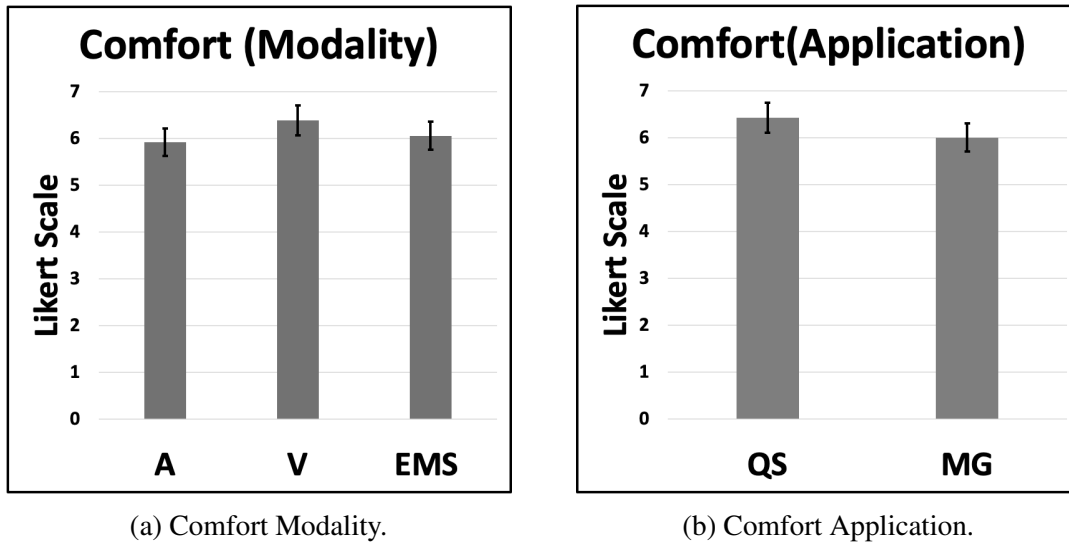


Figure 4.11: User perception of Comfort (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game.

#### 4.5.4 User Perception of Task Disruption

For H4, the main effect for modality type yielded an  $F(2, 68) = 0.036$ ,  $p > 0.05$ , indicating no significant difference between Audio ( $M = 2$ ,  $S.D = 1.37$ ), Vibro-tactile ( $M = 2.11$ ,  $S.D = 1.30$ ), and EMS modalities ( $M = 2.28$ ,  $S.D = 1.65$ ) as illustrated in Figure 4.12a. The main effect for application type yielded an  $F(1, 34) = 0.280$ ,  $p > 0.05$ , indicating that the effect of application type was not significant between quiet standing ( $M = 1.7$ ,  $S.D = 1.05$ ), and mobile game ( $M = 2.51$ ,  $S.D = 1.67$ ) as illustrated in Figure 4.12b. The interaction effect was not significant  $F(2, 68) = 1.427$ ,  $p > 0.05$ . As no significant differences were found in the main effects for modality or the application type, neither modality nor application had any influence on task disruption. As a result, we accept H4.

Table 4.5: 2-Factor ANOVA: User Perception-Task disruption (TD). M: Modality, A: Application.

Source	TD	p
M	$F(2,68) = 0.036$	0.965
A	$F(1,34) = 0.280$	0.6
M X A	$F(2,68) = 1.427$	0.247

Note: \* indicates significant difference  $p < 0.05$ .

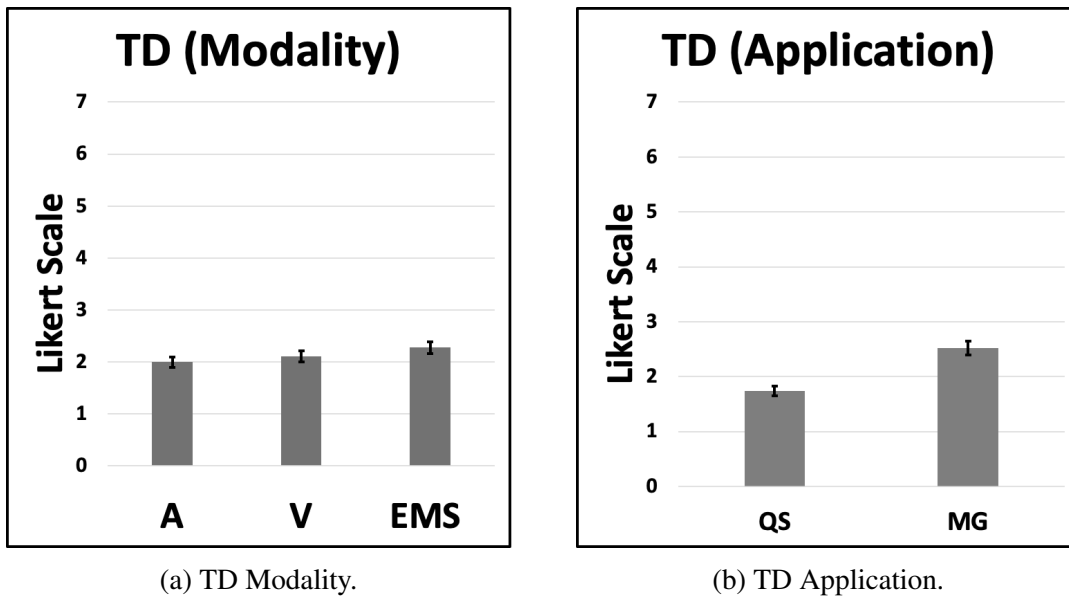


Figure 4.12: User perception of Task Disruption (a) Modality, & (b) Application type. Error bars: 95% CI. A: Audio, V:Vibro-tactile modality, QS: Quiet Standing, MG: Mobile Game.

#### 4.5.5 User Perception and Preference

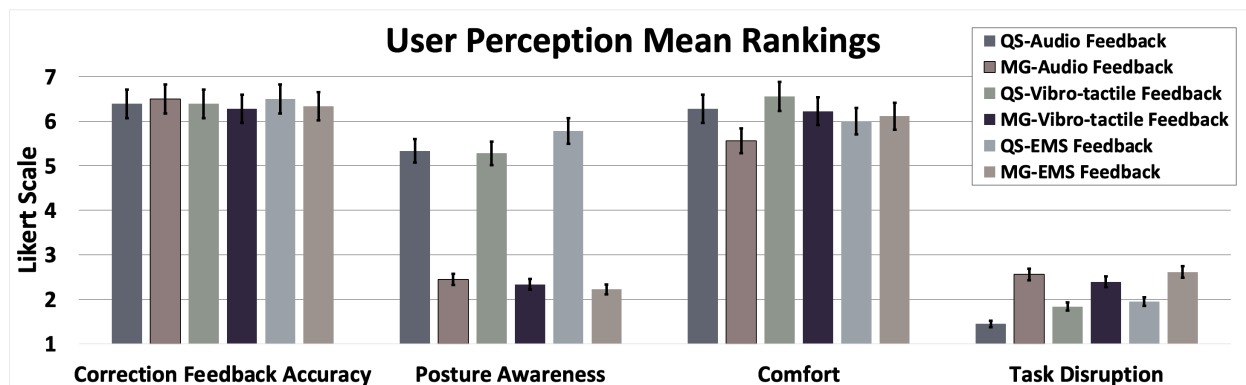


Figure 4.13: User perception mean rankings for correction feedback accuracy, posture awareness, comfort, and task disruption across all modality and application types. Likert Scale: 1-meaning not at all, 7-meaning completely. QS:Quiet Standing, MG:Mobile Gaming. Error bars: 95% CI.

Mean rankings for user perception of correction feedback accuracy, posture awareness, comfort, and task disruption are shown in Figure 4.13. Participants ranked their posture awareness on a 7-point scale where 1 means not at all aware and 7 means completely aware. Participants' ranking indicated higher posture awareness ( $M = 5.46$ ,  $S.D = 1.61$ ) in the quiet standing task, while posture awareness was significantly reduced for the mobile game condition ( $M = 2.33$ ,  $S.D = 1.27$ ). Additionally, when participants were asked about their preferred modality for correcting AWD, 55.56% of the study population reported that EMS feedback was their preferred correction feedback technique, while 36.11% preferred the vibro-tactile feedback and 8.33% preferred the audio feedback. However, 29 out of 36 participants reported that they would be willing to purchase EMS feedback for AWD posture correction if it were a commercially available product. Participants also ranked their shared responsibility with auto-correction utilizing EMS on a 7-point scale where 1 means not at all and 7 means completely. The mean shared responsibility exhibited by the participants was 2.00 ( $S.D = 1.08$ ) in the quiet standing task, and 1.72 ( $S.D = 0.75$ ) for mobile game condition.

Participants ranked EMS feedback to be a highly interesting concept for automatic AWD correction with a mean ranking of 6.33 ( $S.D = 1.39$ ) on a 7-point Likert scale.

## 4.6 Discussion

Given the recent developments of EMS feedback in accelerating preemptive reflexes [93, 94, 153], and slouching posture correction [95], we were interested in understanding if EMS feedback could be utilized for correcting AWD. In comparison to the alternative techniques, we find there are several benefits to automatic correction using EMS. Our approach was able to achieve significantly faster correction at a high accuracy while delivering an equally comfortable user experience across different tasks with different levels of engagement and posture awareness. Although research on postural control, sway analysis, and AWD alert systems have been conducted, the system's correction responsiveness and user perception have not been measured or reported. Therefore, our study primarily focuses on evaluation of the performance and user perception of our EMS feedback based automatic AWD detection and correction technique against traditional audio and vibro-tactile feedback mechanisms.

Correction response times were measured from the time correction feedback is activated until balance has been restored. The average correction response times were significantly faster for the EMS feedback modality in comparison to the audio and vibro-tactile modalities. In both application types, the EMS modality delivered faster AWD corrections leading to faster stabilization and restoration of balance as illustrated in Figure 4.14. This was also reflected in the participants' comments on EMS: "*the fastest feedback and made me correct the best*", "*liked the fast response*", and "*Perfect response, subtle but noticeable*". The faster correction response times to EMS feedback could be mainly due to the automatic stabilization and balance restoration which does not require the user to place emphasis on processing audio or vibro-tactile feedback prior to engaging in a

self-assessment and self-correction process. This self-assessment and self-correction process in the audio and vibro-tactile feedback mechanisms place an additional cognitive load on the user while being engaged in their task and rely entirely on the user’s willingness or intent to self-correct their posture. One participant’s comment attests to this fact: *“Audio-took me time to process the feedback command and then correct, Vibration- got my attention, EMS-pulling quickly didn’t need my attention”*. On the contrary, EMS feedback which does not require the participants’ attention in the correction process, thereby allowing one to continue leveraging the cognitive or attentional resources for the primary task which would have otherwise been required for auditory, visual or sensory processing for postural control. Results also indicate that application type had no effect on the correction response times suggesting that EMS would be capable of delivering faster correction responses across a range of applications with varying levels of engagement and posture awareness. This frees up the cognitive demand of the visual, vestibular and proprioception placed on the user and makes it especially beneficial as a smart intervention technique for athletes in post-operative rehabilitation to prevent unnecessary AWD conditions that prohibit or impede recovery, mitigating risk of re-injury, rebuilding strength and motion, and restoring normal function thereby ensuring proper recovery and safer return-to-sport.

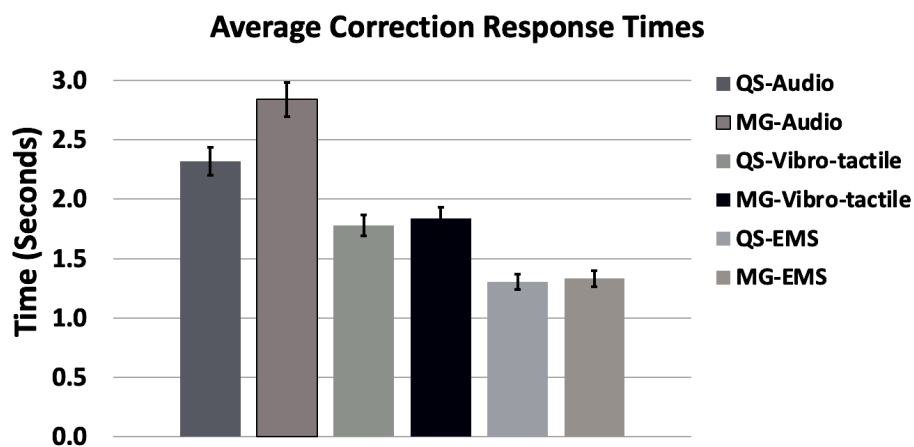


Figure 4.14: Average Correction Response times across all modality and application types. Error bars:95% CI.

Participants' ranking of their perceived accuracy of correction feedback indicated that EMS feedback was more accurate than the audio, and equally accurate in comparison to the vibro-tactile feedback. Some of the participants' comments reflected this fact: *"Audio was most distracting"*, *"EMS was a better form of feedback, was strong and detected even the slightest imbalance"*, *"EMS gave me best feedback, I couldn't hear the audio feedback over the game"*, *"EMS most accurate and best for correction, but could be uncomfortable for some people"*. The participants perceived accuracy of EMS and vibro-tactile feedback equally well and this may have been due to the nature of explicit somatosensory confirmation provided by these two feedback types during delivery and termination of correction feedback when AWD is detected and AWD is corrected, respectively. This illustrates that participants perceived both vibro-tactile and EMS feedback equally accurately due to the distinct and discrete somatosensory experience they offered.

Participants' ranking of their perceived level of comfort and task disruption, indicated neither modality nor application had any influence on the user comfort or task disruption. Although, both EMS and vibro-tactile feedback types are non-invasive in nature, EMS feedback has been known to produce a stronger somatosensory experience due to its ability to produce an involuntary muscular contraction along with a vibro-tactile effect. However, participants perceived all three modalities to be equally comfortable and equally disruptive. This could be due to careful calibration for an optimal EMS intensity that provides the user with a comfortable experience while generating a physiological response to effect a counter-weight shift. This user perception of comfort and task disruption illustrates participants' acceptance of EMS feedback as a viable alternative to the traditional feedback mechanisms with the additional advantage of automatic posture correction freeing up cognitive resources to focus on more important tasks. Participants comments show that EMS *"took time getting used to. It is like an Assisted PUSH, very useful when physical awareness is lacking"* and *"The pulling effect surprised me a bit but it was fine after"*. This acceptance shows EMS feedback's potential to be developed as a commercial product not only for rehabilitation,

intervention, and preventive health care sectors, but also for everyday use by people who are prone to long standing hours due to work or recreational activities. This fact was also supported by the participants' willingness (80.55% of healthy study population) to purchase EMS based wearable AWD intervention technology if it were available as a commercial product.

Participants' ranking of their posture awareness during the two applications indicated that posture awareness was significantly lacking in the mobile game application in comparison to the quiet standing application due to the higher level of engagement and was not affected by the influence of modality type. This finding illustrates the fact that participants perceived EMS feedback as a potential alternative intervention technique in both highly posture aware and highly engaging tasks. This allows our system to be developed into a smart wearable intervention such as smart shoes or socks with capabilities to deliver discrete feedback and correct posture at the same time. Also, this would allow EMS-based smart intervention wearable technology to be available for everyday use especially by younger adults engaging in the use of mobile devices for gaming, social media consumption while standing, and older adults engaging in work related activities in industrial, manufacturing or customer service sectors that require long standing hours.

It was also interesting to note that the EMS intensity required for effecting counter-weight shift by stimulating the tibialis muscles was higher in comparison to another study on automatic detection and correction of slouching [95] where slouched posture was corrected by stimulating the rhomboid muscles (*Mean EMS intensity: Tibialis = 51.25 mA, Rhomboid = 43.47 mA*). This may be because the trapezius muscle is more accessible physiologically in comparison to the tibialis muscle which is regarded as more deeper muscle group and thereby necessitating higher EMS intensity to recruit the motor neurons to cause an involuntary muscular contraction and generate a physiological response for producing the counter-weight shift effect with the desired magnitude and in the desired direction. Participants also reported shared responsibilities in helping/aiding the correction process during the EMS feedback session. This illustrates the participants' adaptability to new



technology and demonstrates the positive learning effect produced by the EMS feedback towards better postural control. Further, it also demonstrates that EMS feedback with its somatosensory feedback encouraged the participants to get involved in the correction process. One participant reported that EMS was *“much faster than the other feedbacks, tingling sensation helps understand the message”*, while another user commented that *“It’s like trainer wheels on a bicycle”*. Finally, some participants commented that EMS *“Felt amazing”*, *“Auto-correction is good”*, *“the fastest feedback and made me correct the best”*, and *“correction happens without thinking about it”*.

Our system could be particularly beneficial in preventive health care and the development of rehabilitation protocols for recovery post-knee/ankle surgery as it would allow the healthcare specialists to develop customized recovery protocols for different individuals by varying the balance and time thresholds, and EMS intensity parameters as prescribed. This would ensure precision control of the weight distribution on the operated leg at different stages of recovery to maximize rebuilding strength and mobility, and minimizing the time duration for return-to-sport in case of athletes or return-to-normal function in case of non-athlete patients. Also, our EMS feedback system when integrated with load sensors and IMUs to be embedded in to shoes, could be utilized to detect AWD and dangerous tilt angles for automatic fall prevention in older adults, and PD patients who present a higher risk of injury due to falls experienced through the loss of balance. Therefore, our autonomous AWD detection and correction system could be a useful alternative or inclusion to the existing environment, health, and safety (EHS) guidelines for mitigating risk of workplace injury, improving employee health, and in rehabilitation and preventive health care.

In conclusion, we have demonstrated that our physiological feedback loop based on automatic AWD detection and correction with EMS is a viable approach to supporting AWD correction, and stabilizing balance through a counter-weight shift approach. Our auto-correction system utilizing EMS feedback demonstrated significantly faster posture correction response times compared to the self-correction in the audio and vibro-tactile feedback. Our approach also showed that participants

perceived EMS feedback to be highly accurate, equally comfortable, and produced no more disruption than the alternative techniques it was tested against in both the quiet standing and the mobile game applications even though the posture awareness across the application types were significantly different. Therefore, automatic AWD detection and correction utilizing EMS shows promising results and can be developed as an alternative method for AWD correction.

The next chapter presents the design and development of an automatic ILP detection and correction utilizing EMS and human subject study conducted to evaluate the effectiveness of our automatic approach.

## CHAPTER 5: AUTOMATIC DETECTION AND CORRECTION OF IMPROPER LOADING POSTURE (ILP)



Figure 5.1: Improper loading posture can lead to lower back injuries and pain. Presented here are images of improper loading posture (A) & (B), corrected posture using Electrical Muscle Stimulation (C), and completion of the lifting activity (D-I).

Improper loading posture is one of the most significant dynamic poor postures, is the leading cause for lower back injuries, and is experienced by nearly 80% of the population at some point in their lives. From the literature, the existing wearable intervention technology for ILP only offer

detection and alert through traditional feedback mechanisms, or provide lift assistance through motorized exoskeletons. As a result, users' are required to either self-correct their ILP when alerts are presented to them or wear relatively bulky assistive exoskeleton systems conspicuously over their clothing, which can be undesirable. For all these reasons, the development of an autonomous improper loading posture detection and correction systems capable of automatically detecting improper lift posture as soon as it starts and subsequently correcting this posture can turn out to be crucial in preventing risk of injury. Additionally, EMS demonstrated its capabilities to correct torso posture in Chapter 3, and restore balance through correcting lower body posture in Chapter 4. This has presented an opportunity to extend the posture auto-correction capabilities of EMS to a dynamic activity poor posture such as ILP during lifting activities to mitigate the risk of injury to the lower back, knees, and ankles.

To address the issue of detecting and automatically correcting ILP, we developed a physiological feedback loop-based wearable intervention prototype relying on IMU sensors and EMS (illustrated in Figure 5.2). Our prototype employed three Metawear MMR wireless sensors for measuring angular changes in human posture, and the *openEMSstim* package [121] for presenting the EMS correction feedback for restoring healthy posture during lifting activities. To complete the physiological feedback loop, a C#-based user interface using Metawear C# SDK was developed for monitoring the posture information from the IMUs and integrated with the EMS hardware for presenting correction feedback when poor lifting postures are detected. Improper loading posture is mainly characterized by an excessive inclination of the torso, and insufficient knee bending [90] (illustrated in Figure 5.1 (A)). To monitor the torso inclination, IMU 1 is placed at the center of the collar bone above the chest (illustrated in Figure 5.3 (A)), and to monitor the knee bend angles, the other IMU's 2 and 3 were placed on each knee (illustrated in Figure 5.3 (B) & (C)).

The change in posture is calculated from the angular information obtained from the IMU sensors. The user's torso inclination angle is calculated from the pitch of IMU1, and the knee bend angles

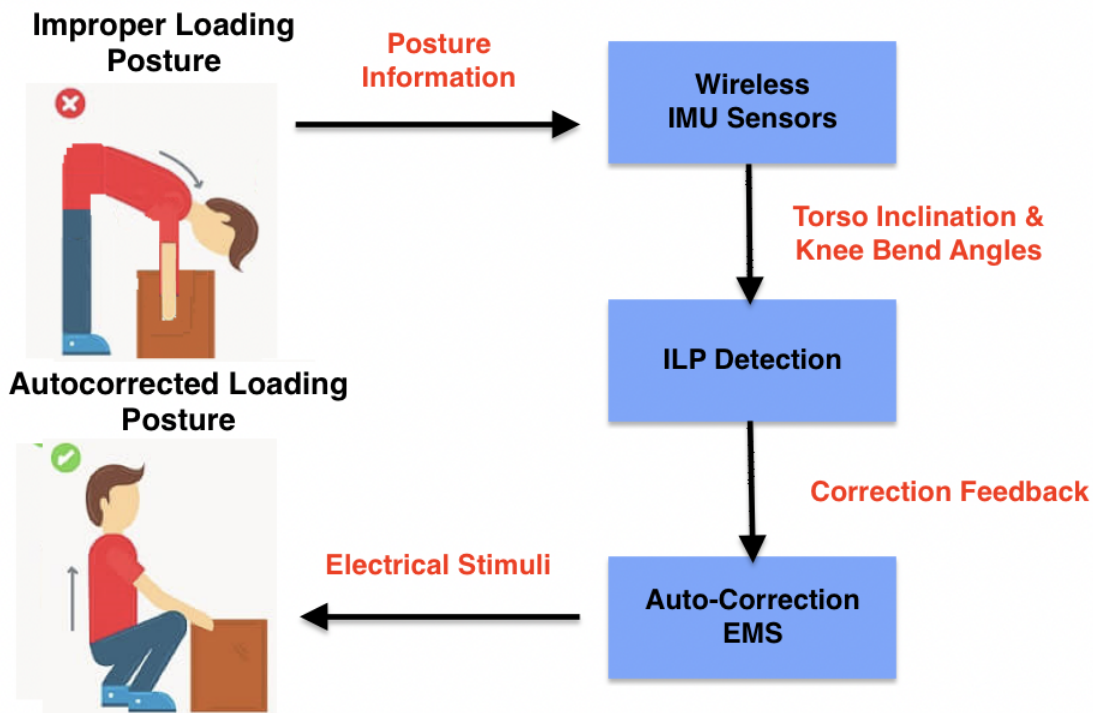


Figure 5.2: Physiological Feedback Loop: Automatic Improper Loading Posture Detection and Correction System. Improper loading posture (top) illustrates excessive torso inclination and insufficient knee bending that can lead to long term low back pain and the auto-corrected posture (bottom) illustrates the restored proper lifting posture achieved through using EMS.

are calculated from the average of pitch of IMU's 2 and 3. To determine the extent of ILP in young adults, we collected ecologically valid data from 10 participants (Male=7, Female 3) and mean age of 21.8 years (S.D= 3.9 years). We measured their maximum torso inclination and maximum knee bend angles in a task involving lifting 4 different boxes of different sizes and weights illustrated in Table 5.1 below. All participants were required to lift the four boxes three times in a random order. and their maximum torso inclination and knee bend angles were recorded. The torso inclination and knee bend angular patterns of young adults while lifting each of the four boxes are illustrated in the Figure 5.4.

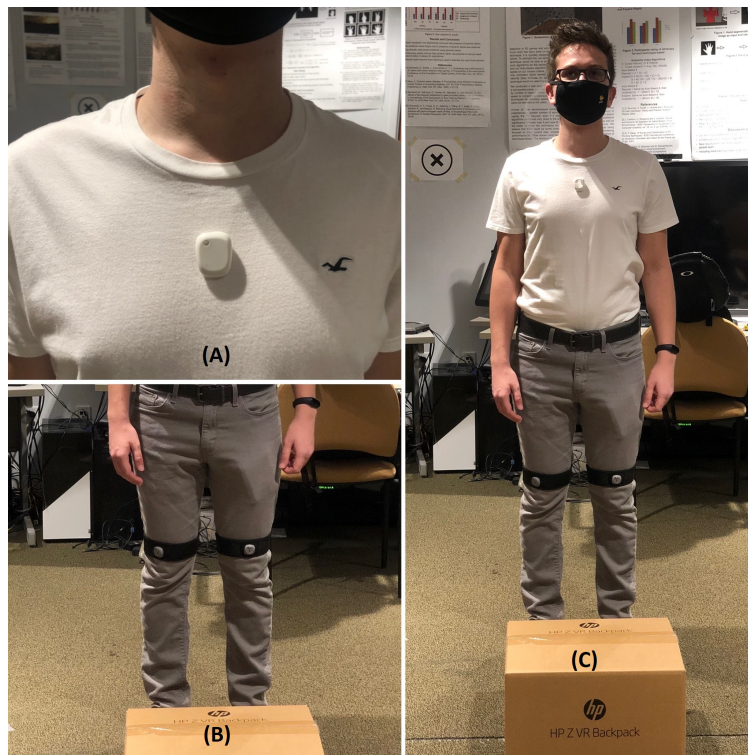


Figure 5.3: Wireless IMU sensor placement for improper loading posture detection: (A) Front view showing sensor placement below center of collar bone above the chest, (B) Front view showing sensor placement above each knee, (C) Front view showing sensor, box placement and experiment set up.

Table 5.1: Size and Weight of Boxes.

Box	Weight (Kg)	Weight (lbs)	Size (LxWxH) cm	Size (LxWxH) in
Box1	2.27	5	25.4 x 25.4 x 16.5	10 x 10 x 6.5
Box2	4.54	10	38.1 x 30.48 x 25.4	15 x 12 x 10
Box3	6.8	15	43.18 x 27.94 x 27.94	17 x 11 x 11
Box4	9.07	20	53.34 x 38.1 x 40.64	21 x 15 x 16

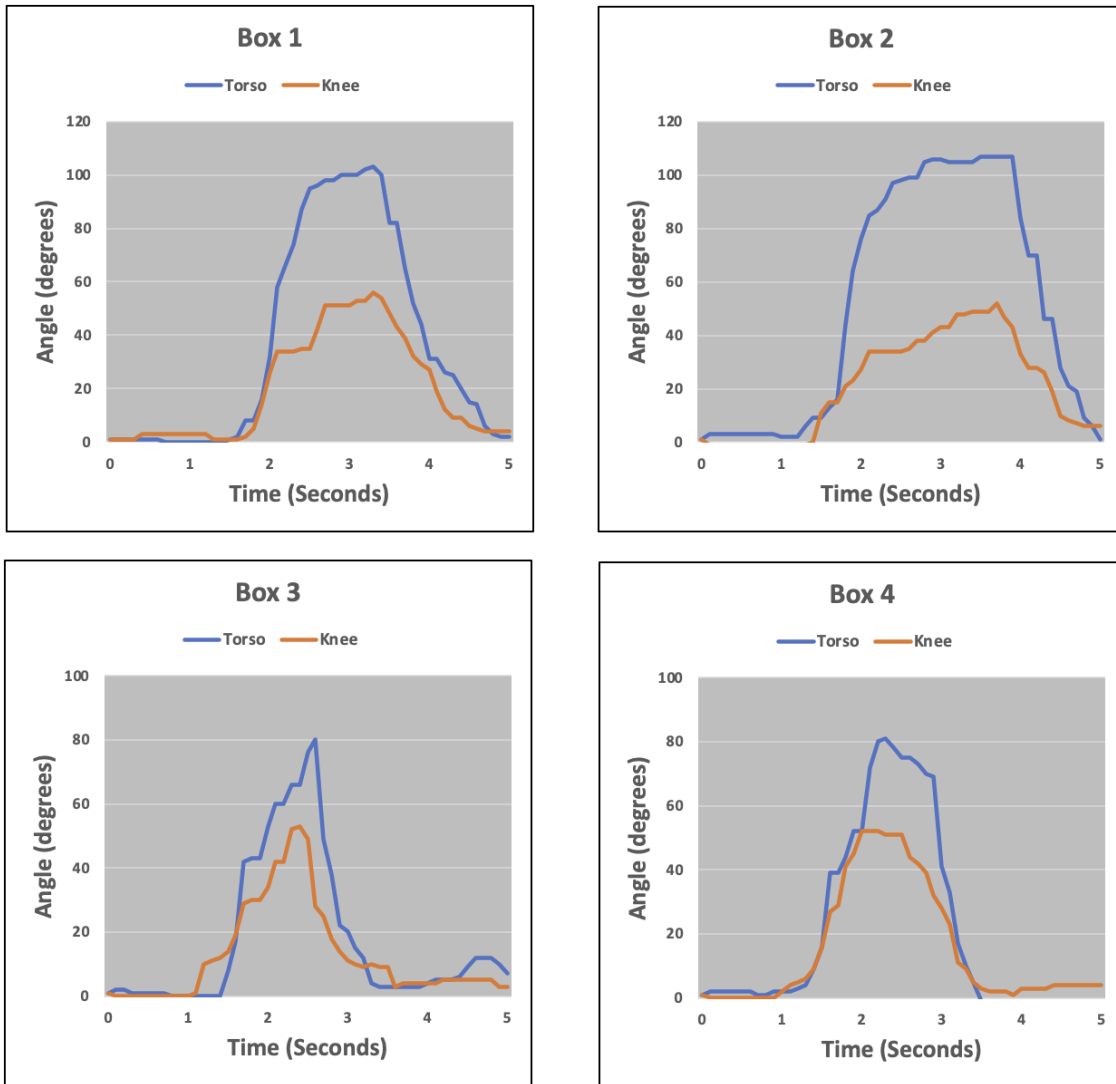


Figure 5.4: Torso inclination and knee bend angular change patterns exhibited by young adults while lifting each of the four boxes.

The average maximum torso inclination angles and maximum knee bend angles among young adults from a general population are calculated and illustrated in figures 5.5 and 5.6 below.

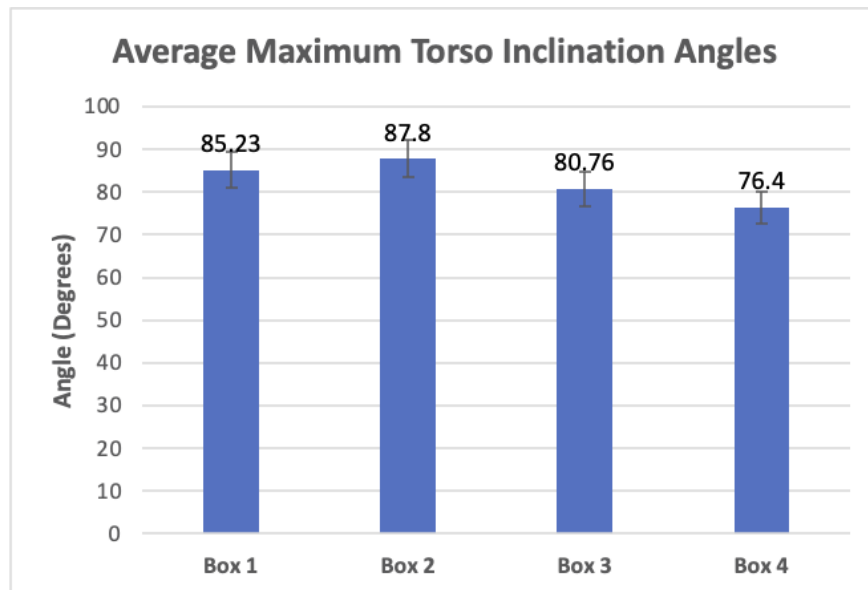


Figure 5.5: Average maximum torso inclination angles exhibited by young adults while lifting different boxes of different weights and sizes. Error bars:95% CI.

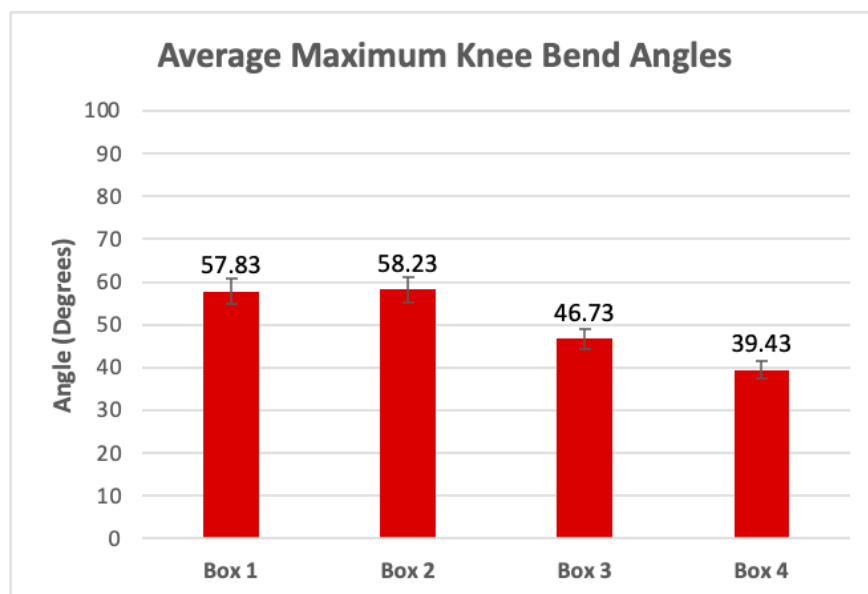


Figure 5.6: Average maximum knee angles exhibited by young adults while lifting different boxes of different weights and sizes. Error bars:95% CI.



## 5.1 Torso Inclination and Knee Bend Angle Thresholds

Improper loading posture can be detected from measuring the offset between actual, and ideal torso inclination and knee bend angles. Our proposed system detected ILP when the user's torso inclination is greater and knee bend angles is lower than the ideal torso inclination and knee bend angles. To determine the ideal torso and knee bend angles for each box, we collected ecologically valid torso inclination and knee bend angles during the same task from five certified fitness trainers (Male=3, Female=2) at the *Recreation and Wellness Center* at University of Central Florida with a mean age of 21.4 years (S.D=1.9 years). All trainers were certified by the following organizations: AFAA <sup>1</sup>, NASM <sup>2</sup>, NSCA <sup>3</sup>, and ACSM <sup>4</sup>. All trainers were required to perform the same task of lifting the four different boxes of different weights and sizes illustrated in the table 5.1. Each trainer performed the task of lifting the four boxes three times in a randomized order. The trainers were required to maintain good lifting posture during their lifting tasks and their torso inclination and knee bend angles were recorded for each box. The trainer torso inclination and knee bend angular patterns during lifting each of the boxes is illustrated in Figure 5.7. The average maximum torso inclination and knee bend angles of the trainers for each box are illustrated in Figures 5.8 and 5.9 below.

The two validation studies indicate a contrast in lifting techniques by young adults and certified trainers. The certified trainers demonstrated good lifting techniques with torso inclination angles of 47°, 47.3°, 38°, and 38.67° for boxes 1, 2, 3, and 4 respectively while the young adults had torso inclination angles of 85.23°, 87.8°, 80.76°, and 76.4° for boxes 1, 2, 3, and 4 respectively. The knee bend angles of the trainers was 88.33°, 84.67°, 81.67°, and 63.33° for boxes 1, 2, 3, and

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<sup>1</sup><https://www.afa.com/>

<sup>2</sup><https://www.nasm.org/>

<sup>3</sup><https://www.nasca.com/>

<sup>4</sup><https://www.acsm.org/>

4 respectively while the young adults had torso inclination angles of 57.83°, 58.23°, 46.73°, and 39.43° for boxes 1, 2, 3, and 4 respectively.

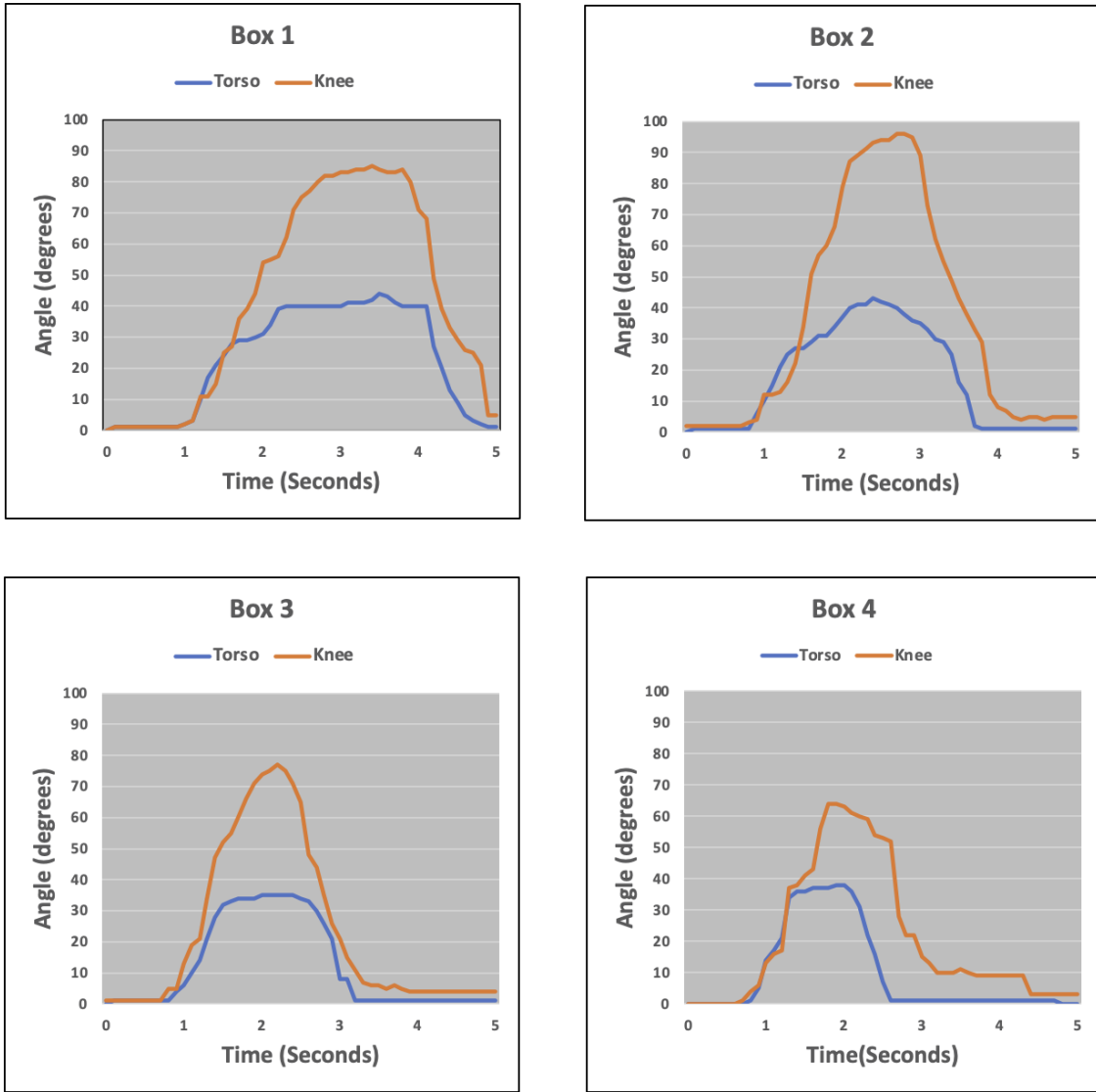


Figure 5.7: Torso inclination and knee bend angular change patterns exhibited by certified trainers while lifting different boxes of different weights and sizes.

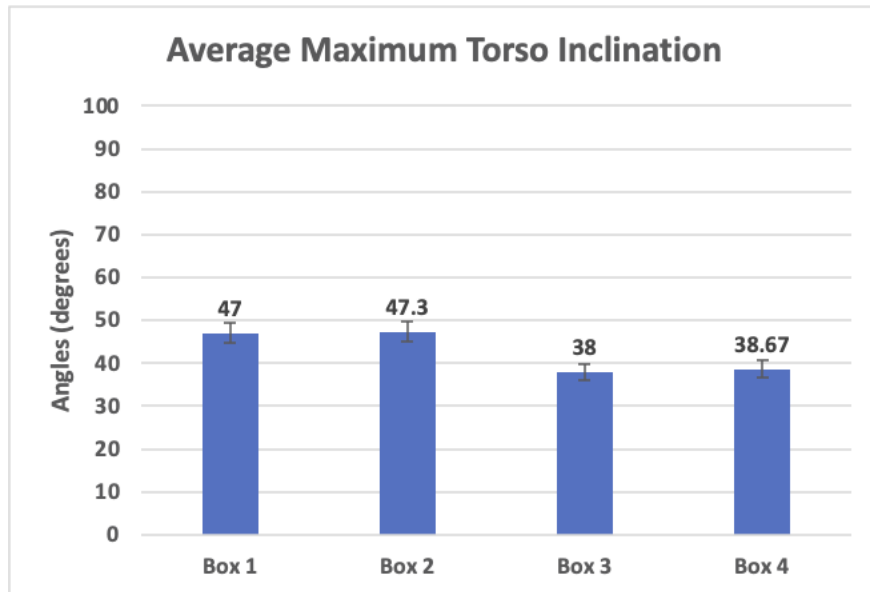


Figure 5.8: Average maximum torso inclination angles exhibited by certified trainers while lifting different boxes of different weights and sizes. Error bars:95% CI.

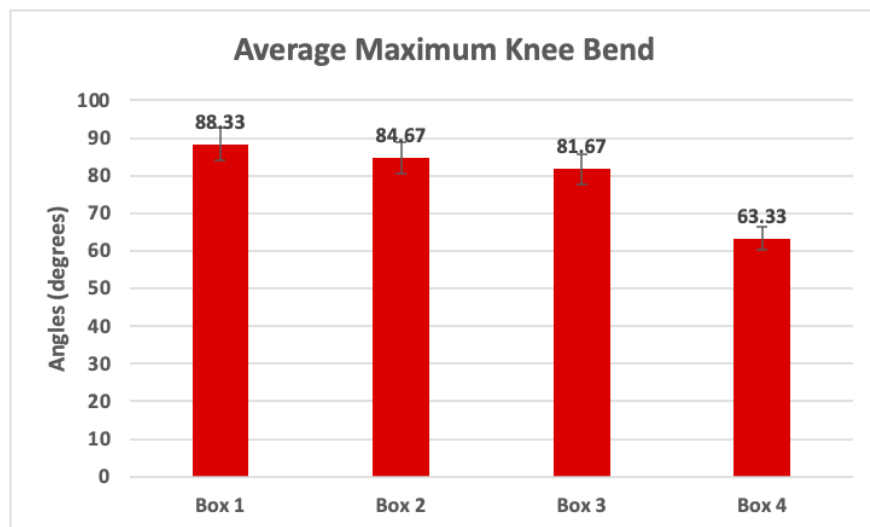


Figure 5.9: Average maximum knee angles exhibited by trainers while lifting different boxes of different weights and sizes. Error bars:95% CI.

The ideal angles demonstrated by the trainers using good lifting posture showed lower torso inclination ranging between 38° to 48° and the higher knee bend angles ranging between 63° to 88°. The lower torso inclination angles are representative of straight and upright torso position and the higher knee bend angles indicate greater knee bending which allows the user to leverage the weight of the load using the stronger hamstring muscles. On the contrary, the young adults exhibited high torso inclination angles ranging between 76° to 88° and low knee bend angles 38° to 57°. The higher torso inclination angles are representative of a bent over improper loading posture, and the lower knee bend angles place higher stresses on the relatively less stronger lower back muscles and vertebrae to complete the lift and hence present a higher risk of injury to the lower back. The difference in the measured torso inclination and knee bend between the trainers and young adults indicated that young adults normally exhibited bent over poor lifting techniques with greater torso inclination and insufficient knee bend. The average maximum torso inclination and knee bend angles exhibited by the certified trainers for the different boxes were recorded and utilized to preset thresholds as ideal torso inclination and knee bend angles in our ILP detection system to improve the detection of poor lifting posture or ILP. These thresholds were chosen to overcome measurement errors and ensure random movements do not lead to false positive improper loading posture detection. The threshold torso inclination and knee bend angles were used to initiate the feedback loop and present the correction feedback.

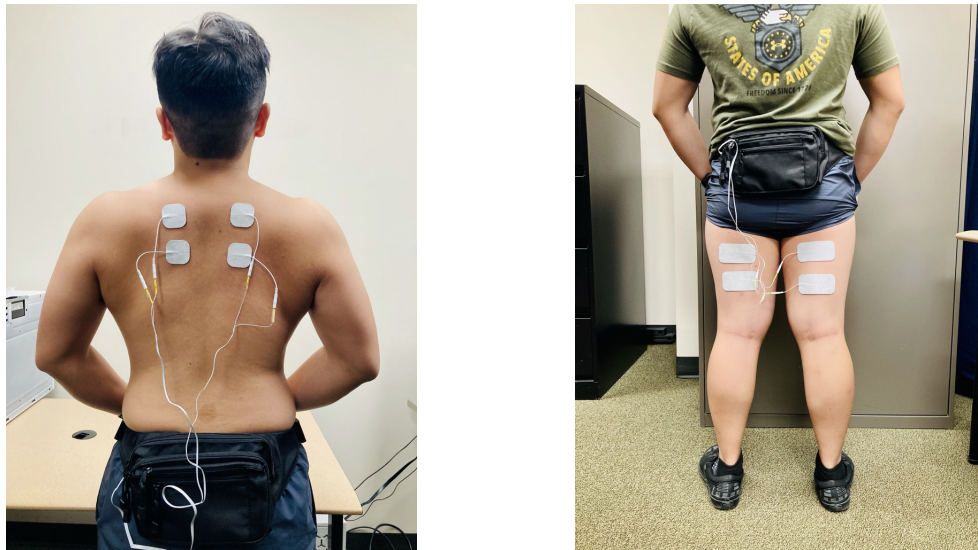
## **5.2 Correction Feedback**

Subsequently, when improper loading posture was detected, we employed two separate posture correction strategies to automatically restore proper loading posture by applying EMS to the two different affected locations separately as follows:

- Torso Inclination Correction

- Knee Bend Correction

The torso inclination correction is achieved by applying EMS to the rhomboid muscles through a pair of electrodes (illustrated in Figure 5.10a). The knee bend correction is achieved by applying EMS to the hamstring muscles through a pair of electrodes (illustrated in Figure 5.10b).



(a) Electrode placement on Rhomboid muscles. (b) Electrode placement on Hamstring muscles.

Figure 5.10: EMS electrode placement on (a) Rhomboid muscles for torso inclination correction, & (b) Hamstring muscles for Knee bend correction.

## 5.2.1 Correction Strategies

### 5.2.1.1 Torso Inclination Correction

In the torso inclination correction strategy, improper loading posture was detected when the users' current torso inclination and knee bend angles were below ideal torso inclination and knee bend angles recorded from the trainers, and automatic correction through EMS was applied to the

rhomboid muscles to restore ideal torso inclination angles. An involuntary rhomboid muscle contraction generates a pulling force in the opposite direction from the improper torso inclination posture and thereby generates a physiological response to stabilize the torso inclination. As a result of this torso inclination correction, ideal knee bend is effected by the user in order to the reach and pick up the load. Two pairs of electrodes would be utilized for contraction of the rhomboid muscles which causes the shoulders blades to be pulled back and to restore an upright torso at the ideal torso inclination angles.

#### *5.2.1.2 Knee Bend Correction*

Alternatively, in the knee bend correction strategy, improper loading posture was detected when the users' current torso inclination and knee bend angles were below ideal torso inclination and knee bend angles, and automatic correction through EMS was applied to the hamstring muscles to cause an involuntary contraction to produce necessary bend angles at the knees. As a consequence of achieving the ideal knee bend angles, the users' torso inclination is also restored back to ideal torso inclination angles. Two pairs of electrodes would be utilized for contraction of the hamstring muscles (one pair for each hamstring) to cause the knees to bend and cause the knees to bend toward the ideal bend angles. The preset torso inclination and knee bend angle thresholds were determined from the validation study described above in Section 5.1.

Additionally, IMU and EMS calibration play a crucial role in the effectiveness of the system. The calibration process includes correcting IMUs offset value in the upright position of the user and monitoring the angular change in the proper and improper loading posture with respect to the upright position. The EMS intensity calibration would be manually incremented to deliver an intensity that is optimal for generating involuntary muscular contraction and avoid any pain. This EMS intensity provided to the user for generating the necessary involuntary contraction for correcting the improper

loading posture and restoring the proper loading posture would be recorded and utilized during the experiment. The TENS device can deliver intensities between (0-100mA) based on requirement and user comfort. A continuous 75 Hz square wave pulse at the recorded EMS intensity and a pulse width of 100  $\mu s$  is supplied as the electrical stimulus to the users.

### 5.3 Operation

Our physiological feedback loop for detecting and correcting ILP relied on the angular changes from the sensors placed on the torso and knees to measure torso inclination and knee bend angles respectively. ILP occurs when a user attempts to perform the lifting task with a high torso inclination and low knee bend angles. This would be representative of a bent over lifting posture which places an unnecessary stress on the lower back and increases the risk of injury. To detect these improper loading postures, our system utilized the torso inclination and knee bends angles obtained from the trainers as ideal threshold angles for each box. Figure 5.11 illustrates the activation and deactivation of EMS correction feedback when ILP was detected and corrected for a participant during the torso correction strategy part of the study. The participant exhibited ILP (as in Figure 5.1(A)) while lifting Box 3. For Box 3, the ideal torso inclination and knee bend angles (determined in Section 5.1) were  $38^\circ$  and  $81.67^\circ$ , respectively. When the participant's torso inclination exceeded the ideal torso inclination threshold, and the knee bend was sufficiently lower than the ideal knee bend angle for Box 3, ILP was detected. The ILP detection automatically activated the EMS correction feedback by applying a stimulus of 60 mA to invoke an involuntary contraction of the rhomboid muscles for generating a physiological response of stabilizing the torso in an upright position towards the ideal torso inclination angles and this in turn causes the user to bend knees to the ideal knee bend angles in order reach and lift the box with good lifting posture. The EMS was automatically deactivated when the ideal torso inclination and knee bend angles are achieved. A correction response time of

1.3 Seconds was recorded between activation and deactivation of the EMS for torso stabilization. The knee bend correction strategy works similarly to achieve the ideal knee bend angles, which in turn cause the torso to stabilize towards ideal torso inclination angles to establish good lifting posture.

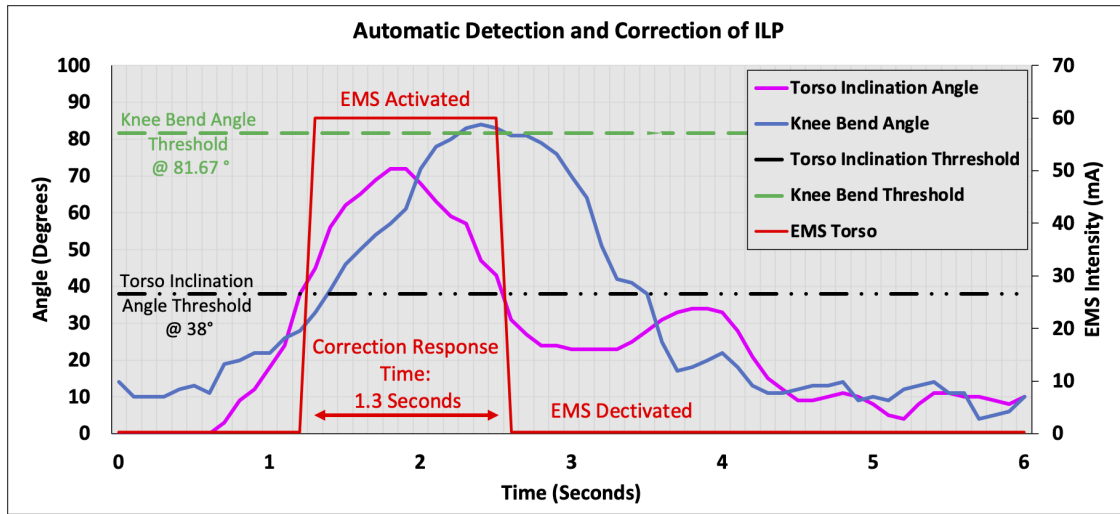


Figure 5.11: Automatic Detection and Correction of ILP: Graph showing EMS activation and deactivation. When ILP is detected from the user’s high torso inclination and low knee bend angle, EMS was activated on the torso/knees for ILP correction. EMS was deactivated when ideal torso inclination and knee bend angles are achieved.

We conducted two studies to evaluate the effectiveness of our automatic ILP detection and correction based on EMS feedback, and also the effect of the two correction strategies on user perception. In the first study, participants emulated ILP while performing the lifting task to receive the correction feedback for determining the effectiveness of our automatic approach. In the second study, the participants performed ecologically valid lifting where participants were free to perform the lifting tasks in their own natural way. In both studies, we compared our automatic approach against two alternative feedback systems (audio and vibro-tactile) requiring self-correction, and across both correction strategies. In both studies, we also evaluated the user perception of correction feedback, comfort, disruption, posture awareness, and preferences.

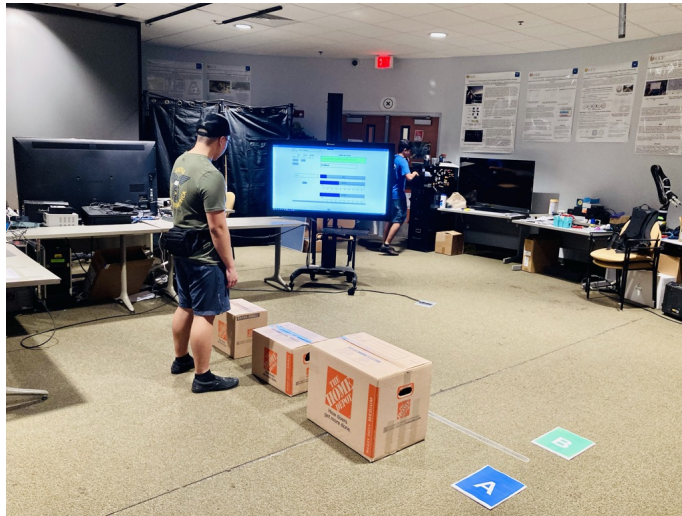


## 5.4 Methods: Study 1

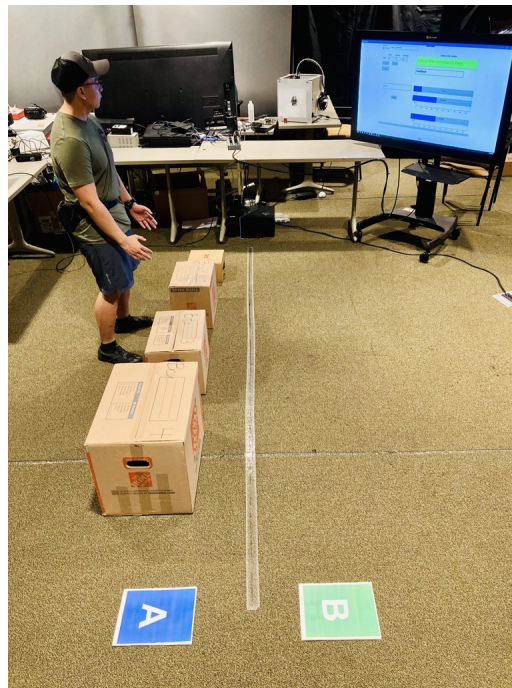
The first study was a 2 by 3 within subjects study (24 participants) where all participants were required to complete the lifting tasks with all 3 feedback modalities (Audio, Vibro-tactile, and EMS) across the 2 correction strategies (Torso inclination correction, and Knee bend correction). In this study, participants emulated improper loading posture with high torso inclination and low knee bend (as illustrated in Figure 5.1 (A)), and self/auto-corrected their posture by achieving ideal torso inclination and knee bend angles (as illustrated in Figure 5.1 (C)) when correction feedback was presented. The objective of this study was to determine the effectiveness and accuracy of the ILP detection and automatic correction in an emulated task of moving four different sized boxes with different weights from one location to another. The experimental set up is illustrated in Figures 5.12a & 5.12b.

### 5.4.1 Subjects and Apparatus

We recruited 24 participants (Male=17 , Female=7). All participants were aged 18 years and above with a mean age of 22.7 years ( $S.D = 4$ ), mean weight of 71.2 Kg ( $S.D = 9.72Kg$ ), and mean height of 171.5cm ( $S.D = 9.6cm$ ). All participants were able bodied and had no upper and lower body injuries. For monitoring the torso inclination and the knee bend angles, three Metawear MMR IMU sensors were utilized. The Metawear MMR IMU sensors contain an inbuilt vibration motor for delivering vibro-tactile feedback notifications. The EMS would be generated with an off-the-shelf Tens unit and controlled by the *openEMSstim* package for activating and modulating the intensity of the electrical stimuli supplied to the muscles. The hardware used for the study user interface was a 14” Intel i7 Laptop, and a Microsoft Surface 50 inch display screen was utilized to display commands to the participants. Four boxes of different sizes and weights were utilized for the study. The size and weight of the boxes are illustrated in the Table 5.1. From the pre-questionnaires,



(a) Experimental Setup.



(b) Experimental Setup - Side view.

Figure 5.12: Experimental setup showing the four different sized boxes with different weights that need to be moved from zone A to B, and vice versa based on instructions presented to them via a Microsoft Surface 50 inch display placed in front of them.

participants' ranking of their prior exposure to posture alert devices and EMS, experience with posture problems, and improper loading posture was noted and illustrated in Table 5.2. Participants ranked their exposure and experience on a 7-point scale with 1 meaning never/no experience and 7 meaning frequently/very experienced.

Table 5.2: User ranking on lifting tasks, ILP, alert devices, and EMS. User ranking on a 7-point Likert scale.

<b>User Experience</b>	<b>Mean</b>	<b>S.D</b>
Lifting Tasks/Dead Lift/Squats	3.2	2.08
Experienced ILP	3.7	1.26
Exposure to ILP alert devices	2.5	1.74
Exposure to EMS	1.79	1.10

#### 5.4.2 *Experimental Design*

A 2 by 3 within subjects experiment with 24 participants was conducted to investigate the performance and feasibility of our approach. The within subject factor was the feedback type (Audio, Vibro-tactile, and EMS) and the between-subject factor was the correction strategy (Torso inclination correction, and Knee bend correction). We compared the performance of our automatic improper loading posture correction using the EMS feedback against the self- correction in the audio and vibro-tactile feedback techniques. Average correction response times and user perception of the system across the two correction strategies and the three feedback types were evaluated.

### 5.4.2.1 Task

To determine the effectiveness of our approach, all participants had to perform the following task with improper lifting posture to experience the different correction feedbacks and correction strategies:

- Lift each box from zone A, move to Zone B, and place box in Zone B.
- Lift each box from zone B, move to Zone A, and place box in Zone A.

The order in which the participants moved the boxes from Zone A to Zone B was randomized and the participants were given instructions on performing a bent over improper loading posture with high torso inclination and low knee bend as illustrated in Figure 5.13(A). Figure 5.13 illustrates an example of participant following the instructions to lift, move and place a random box.

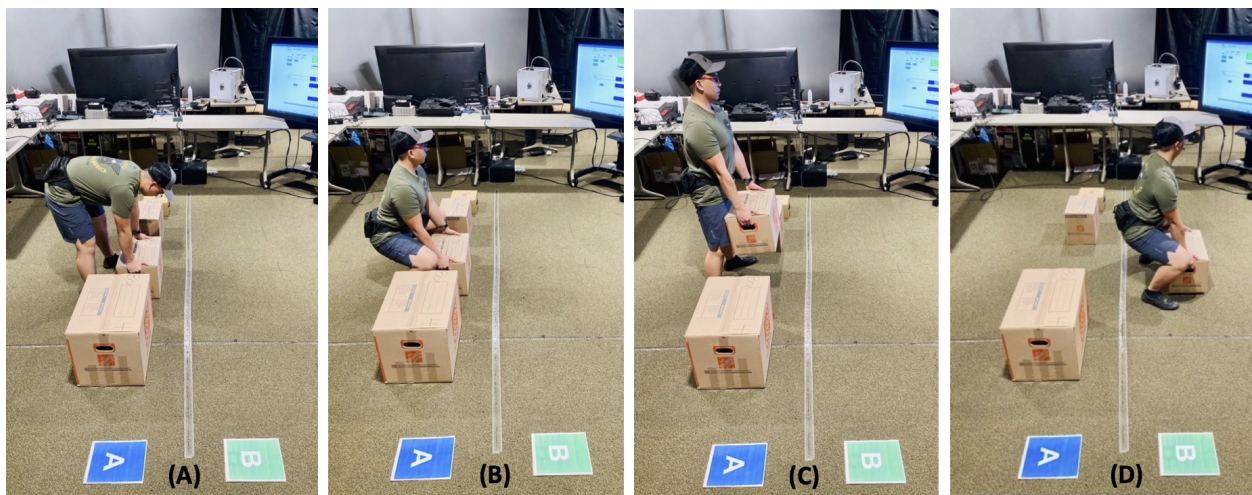


Figure 5.13: An example of participant performing the task: (A) Lifting box 3 with ILP from Zone A, (B) Receiving correction feedback to restore proper torso inclination and knee bend lifting angles, (C) Completing the lift, and (D) Moving to Zone B and placing it in Zone B.

The participants were required to lift each of four boxes separately and complete all three feedback modalities and across the two correction strategies as follows.

### **Modalities**

- Modality 1: Audio alert feedback and self-correction
- Modality 2: Vibro-tactile alert feedback and self-correction
- Modality 3: EMS feedback and automatic correction

### **Correction Strategies**

- Torso inclination Correction
- Knee bend correction

In each of the six combinations (2 correction strategies x 3 feedback modalities), participants were required to pick up all the four different boxes in a randomized order to minimize learning effects. The independent variables in the study were the three different feedback modalities and the two different correction strategies. The dependent variables were the average correction response times, and user perception parameters such as overall experience, accuracy of correction feedback, task disruption, comfort, and posture awareness. Each study session lasted approximately 60 minutes and the participants were compensated \$10 for their participation.

### 5.4.3 *Research Hypothesis*

The study was designed to determine the effectiveness of automatic or self-posture correction on user experience across the two correction strategies and the three modalities. As such, we expect significant differences between the three modalities and the two correction strategies which could influence user experience. For investigating into the system performance and user perception, we have four research hypotheses.

- **H1:** Automatic EMS based correction feedback will deliver a faster correction to ILP in comparison to the self-correction based audio, and the vibro-tactile feedback across the two correction strategies.
- **H2:** User perception of correction feedback accuracy in the automatic EMS based correction feedback will be greater than audio, and vibro-tactile feedback across the two correction strategies.
- **H3:** Automatic EMS based correction feedback will deliver an equally comfortable user experience in comparison to audio, and vibro-tactile feedback across the two correction strategies.
- **H4:** No evidence will be found for a difference in task disruption across the audio, vibro-tactile, and EMS correction feedbacks across the two correction strategies.

### 5.4.4 *COVID-19 Considerations*

Due to the ongoing COVID-19 pandemic, we wanted to ensure safety for the participants and researchers. Following our institutions guidelines, all individuals were required to always wear face masks. Between each participant, we sanitized all devices and surfaces that the participants and

researchers would be in contact with, to ensure safety during the study. Furthermore, all users were required to wear a face mask to participate in the study. We also provided hand sanitizer, cleaning wipes, and latex gloves to reduce risk of contracting the disease. Though we cleaned all surfaces between participants, we allowed participants to clean devices as desired.

#### *5.4.5 Experimental procedures*

##### *5.4.5.1 Preparation and Calibration*

Prior to starting the experiment, participants were required to review the consent form that details the experiment, safety, risks, compensation, compliance, and provide consent for the study session to start. Participants then completed a survey on their knowledge and experience on workplace related posture issues, intervention technology, and EMS as illustrated in Table 5.2. Next, IMU sensors were placed on the participants knees and center of the collar bone above the chest (as shown in Figure 5.3 (A) & (B)), for detecting improper loading posture and data collection. Adhesive EMS electrodes were placed on the rhomboid or hamstring muscles prior to the EMS feedback session for torso inclination correction strategy or knee bend correction strategy respectively. Subsequently, IMU sensors were calibrated for each participant and corrected for offset. Correct IMU sensor functioning and operation were verified during the calibration by monitoring the angular changes when participants were in upright, proper, and improper loading positions.

Before the EMS feedback session in both torso inclination and knee bend correction strategies, an EMS intensity calibration process would be done manually for each participant on the respective locations. After electrode placement on the rhomboid or hamstring muscles, moderators would increment the intensity until an involuntary muscular contraction causing posture correction occurs. The participants would be calibrated manually only once for EMS intensity to generate a physio-

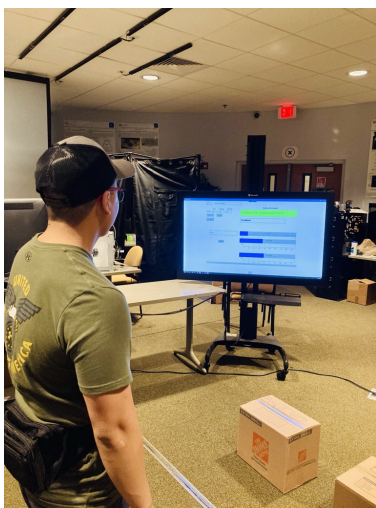
logical response of correcting the torso inclination and knee bending for restoring proper loading posture while picking up the box.

In the case of the torso inclination correction strategy, EMS was applied to the rhombus muscles to invoke an involuntary contraction which generates a physiological response of stabilizing the torso in an upright position. Alternatively, in the case of the knee bend correction strategy, EMS was applied to the hamstring muscles to invoke an involuntary muscular contraction that generates a physiological response of bending the knees. During EMS calibration, participants were asked to emulate an improper loading posture, and moderators manually incremented the EMS intensity applied to the torso and knee independently to cause torso inclination correction, or knee bend correction. As EMS also produced a tactile or haptic effect even at low intensities, participants were asked to not respond to the tactile or haptic effect to ensure the haptic/tactile component of EMS does not contribute to the automatic correction process in any way. Moderators additionally asked participants to verbally respond specifically to the following questions during calibration to ensure rhomboid or hamstring muscular contractions and participant comfort: 1) when they initially felt the stimulation (haptic sensation), 2) when the intensity was generating an involuntary muscular contraction and/or when they experienced a pulling force on their torso in the opposite direction in case of torso inclination correction, and when a downward pulling force causing their knees to bend is experienced due to contraction of their hamstrings in case of knee bend correction, and 3) when any pain was experienced. For each participant, when involuntary muscular contractions were confirmed verbally by the participant and visually verified by the moderators, the optimal EMS intensity that was generating the involuntary muscular contraction to correct the improper loading posture was recorded and selected for the EMS part of the study (Refer section 3.3.3 for more details on the step-by-step calibration process).

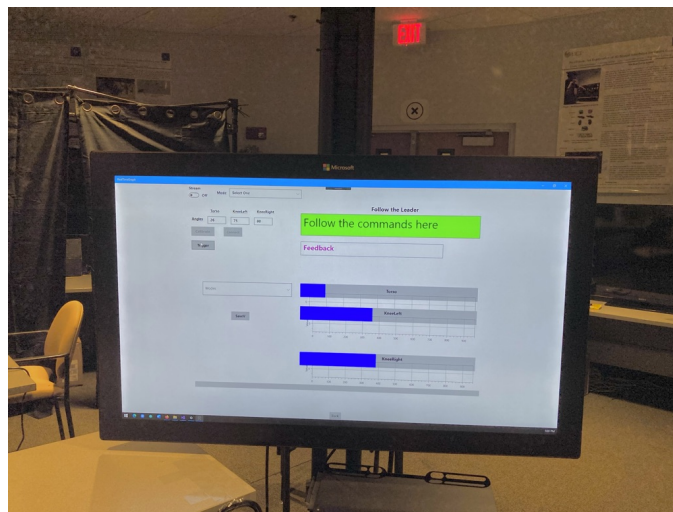


#### 5.4.5.2 Experiment

The study comprises of six parts: audio, vibro-tactile, and EMS feedback for torso inclination correction, and audio, vibro-tactile, and EMS feedback for knee bend correction. Each part of the study is 5 minutes in duration and all participants were required to finish all parts to complete the study. The participants were given a 5-minute break after each part of the study. Participants then completed a survey about their experience after each part and a comparative survey on their overall experience at the end of the study. Participants completed the six parts of the study in a counterbalanced order. In all six parts, participants were required to pick up each of the four boxes separately while emulating improper lifting posture with high torso inclination and low knee bend. The order of the boxes that participants were required to lift were randomized and command prompts were presented using the C# user interface on a Microsoft Surface 50 inch display placed in front of them (illustrated in Figures 5.14a and 5.14b).



(a) Participant view.



(b) C# User interface display.

Figure 5.14: Experimental setup showing instructions presented to participant. (a) Participant view, (b) C# User interface display on Microsoft Surface 50 inch display. Commands to lift and move boxes are displayed in the green display box.

Participants were required to follow the commands presented to them and complete the task as described in section 5.4.2.1. Their loading posture was monitored for ILP detection and application of correction feedback with respect to the modality and correction strategy as illustrated in Figure 5.13.

### **Part 1**

- Correction Strategy: Torso inclination correction
- Feedback Modality: Audio feedback and self-correction

When ILP was detected by the system based on the IMU sensor feedback, an audio notification in the form of a distinct auditory tone was presented to the users, and the users were required to self-correct their ILP by stabilizing their torso towards the ideal torso inclination angle until a second auditory tone indicating corrected posture (with ideal torso inclination and knee bend angles) is presented to the user. The response times for self-correcting ILP were recorded.

### **Part 2**

- Correction Strategy: Torso inclination correction
- Feedback Modality: Vibro-tactile feedback and self-correction

When ILP was detected by the system based on the IMU sensor feedback, a haptic notification in the form of vibration was activated on IMU1 placed on the torso and the users were required to self-correct their ILP by stabilizing their torso towards the ideal torso inclination angle until the haptic vibration notification stops, indicating restoration of proper loading posture (with ideal torso inclination and knee bend angles). The response times for correcting the ILP were recorded.

### **Part 3**

- Correction Strategy: Torso inclination correction
- Feedback Modality: EMS feedback and automatic correction

When ILP was detected by the system, the EMS feedback was activated to apply the recorded EMS intensity to the rhomboid muscles to invoke an involuntary muscle contraction. The rhomboid muscle contraction produces a pulling force in the opposite direction to torso inclination. This generates the physiological response of stabilizing the torso to an upright position towards the ideal torso inclination angle for restoring proper loading posture. Figure 5.13 (A) illustrates the improper loading posture, and Figure 5.13 (B) illustrates the corrected loading posture. The EMS was deactivated immediately when proper loading posture with the ideal torso inclination and knee bend angles have been achieved or restored. The response times for correcting the improper loading posture were recorded.

### **Part 4**

- Correction Strategy: Knee bend correction
- Feedback Modality: Audio feedback and self-correction

When ILP was detected by the system based on the IMU sensor feedback, an audio notification in the form of distinct auditory tone was presented to the users, and the users were required to self-correct their ILP by bending their knees towards the ideal knee bend angles until a second auditory tone indicating corrected posture (with ideal torso inclination and knee bend angles) is presented to the user. The response times for self-correcting ILP were recorded.

## **Part 5**

- Correction Strategy: Knee bend correction
- Feedback Modality: Vibro-tactile feedback and self-correction

When ILP was detected by the system based on the IMU sensor feedback, a haptic notification in the form of vibration was activated on IMU2 and IMU3 placed on the knees and the users were required to self-correct their ILP by bending their knees towards the ideal knee bend angles until the haptic vibration notification stops, indicating restoration of proper loading posture with ideal torso inclination and knee bend angles). The response times for correcting the ILP were recorded.

## **Part 6**

- Correction Strategy: Knee bend correction
- Feedback Modality: EMS feedback and automatic correction

When ILP was detected by the system, the EMS feedback was activated to apply the recorded EMS intensity to the hamstring muscles to invoke an involuntary muscle contraction. The hamstring muscle contraction produces a downward pulling force. This generates a physiological response of bending the knees towards the ideal knee bend angles restoring proper loading posture. Figure 5.13 (A) illustrates the improper loading posture, and Figure 5.13 (B) illustrates the corrected loading posture. The EMS was deactivated immediately when proper loading posture with the ideal torso inclination and knee bend angles have been achieved or restored. The response times for correcting the improper loading posture were recorded. The results from the study are presented in section 5.6.1.

## 5.5 Methods: Study 2

The second study was a 2 by 3 mixed subjects study (36 participants) with 18 participants for each correction strategy (Torso inclination correction and Knee bend correction). Participants were required to complete the lifting tasks with all 3 feedback modalities (Audio, Vibro-tactile, and EMS) in one of the correction strategies. In this study, the participants performed the lifting task in an ecologically valid manner without any instructions on lifting techniques. When ILP was detected by the system, the participants were presented with corresponding correction feedback and were required to self/auto-correct their ILP by achieving ideal torso inclination and knee bend angles (as illustrated in Figure 5.1 (C)) when correction feedback was presented. The objective of the study was to determine the best modality and/or the correction strategy in an emulated task of moving four different sized boxes with different weights from one location to another. The experimental set up is illustrated in Figures 5.12a & 5.12b.

### 5.5.1 Subjects and Apparatus

We recruited 36 participants (Male=22 , Female=14). All participants were aged 18 years and above with a mean age of 22.6 years ( $S.D = 3.6$ ), mean weight of 70.4 Kg ( $S.D = 11.8Kg$ ), and mean height of 170.4cm ( $S.D = 11.2cm$ ). All participants were able bodied and had no upper and lower body injuries. The hardware used in this study are the same as used in study 1. Refer to section 5.4.1 for hardware details. From the pre-questionnaires, participants' ranking of their prior exposure to posture alert devices and EMS, experience with posture problems, and improper loading posture were noted and illustrated in Table 5.3. Participants ranked their exposure and experience on a 7-point scale with 1 meaning never/no experience and 7 meaning frequently/very experienced.

Table 5.3: User ranking on Lifting task, ILP, alert devices, and EMS. User ranking on a 7-point Likert scale. T:Torso inclination correction strategy, K: Knee bend correction strategy.

<b>User Experience</b>	<b>Strategy</b>	<b>Mean</b>	<b>S.D</b>
Lifting tasks/Dead lifts/Squats	T	3.22	2.41
	K	3.44	1.69
Experienced ILP	T	3.78	1.21
	K	3.83	1.29
Exposure to ILP alert devices	T	2.33	1.28
	K	1.94	0.94
Exposure to EMS	T	1.83	1.09
	K	1.89	0.90

### 5.5.2 Experimental Design

A 2 by 3 mixed subjects experiment involving 36 participants with 18 participants for each correction strategy was conducted to investigate the performance and feasibility of our approach. The within subject factor was the feedback type (audio, vibro-tactile, and EMS) and the between-subject factor was the correction strategy (Torso inclination correction, and Knee bend correction). We compared the performance of our automatic ILP correction using the EMS feedback against the self-correction in the audio and vibro-tactile feedback techniques. Average correction response times and user perception of the system across the two correction strategies and the three feedback types were evaluated.

### 5.5.2.1 *Task*

To determine the effectiveness of our approach, all participants had to perform the following task to experience the different correction feedbacks and correction strategies:

- Lift each box from zone A, move to Zone B, and place box in Zone B.
- Lift each box from zone B, move to Zone A, and place box in Zone A.

The order in which the participants moved the boxes from Zone A to Zone B was randomized. The participants were required to lift each of four boxes separately and complete all three feedback modalities in one of the two correction strategies allotted to them as follows:

- Modality 1: Audio feedback and self-correction
- Modality 2: Vibro-tactile feedback and self-correction
- Modality 3: EMS feedback and automatic correction

In each modality, participants would be required to pick up all the four different boxes in a counterbalanced order to minimize learning effects. The independent variables in the study are the three different modalities and the dependent variables are the average correction response times, and user perception parameters such as overall experience, accuracy of correction feedback, task disruption, comfort, and posture awareness. Each study session lasted approximately 20-30 minutes and the participants were compensated \$10 for their participation.

### 5.5.3 *Research Hypothesis*

The study was designed to determine the effectiveness of automatic or self-posture correction on user experience across the two correction strategies and the three modalities. As such, we expect significant differences between the three modalities and the two correction strategies which could influence user experience. For investigating into the system performance and user perception, we have four research hypotheses:

- **H1:** Automatic EMS based correction feedback will deliver a faster correction to ILP in comparison to the self-correction based audio, and the vibro-tactile feedback across the two correction strategies.
- **H2:** User perception of correction feedback accuracy in the automatic EMS based correction feedback will be greater than audio, and vibro-tactile feedback across the two correction strategies.
- **H3:** Automatic EMS based correction feedback will be deliver an equally comfortable user experience in comparison to audio, and vibro-tactile feedback across the two correction strategies.
- **H4:** No evidence will be found for a difference in task disruption across the audio, vibro-tactile, and EMS correction feedbacks across the two correction strategies.

### 5.5.4 *COVID-19 Considerations*

The same COVID-19 considerations were followed as in Study 1. Refer to section 5.4.4 for more details.



## 5.5.5 *Experimental procedures*

### 5.5.5.1 *Preparation and Calibration*

The preparation and calibration phase is the same as in study 1 (refer to 5.4.5.1 for detailed description).

### 5.5.5.2 *Experiment*

The study comprises of three parts: audio, vibro-tactile, and EMS feedback for torso inclination correction strategy or knee bend correction strategy. Each part of the study is 5 minutes in duration and all participants were required to finish all parts to complete the study. The participants were given a 5-minute break after each part of the study. Participants then completed a survey about their experience after each part and a comparative survey on their overall experience at the end of the study. Participants completed all three parts of the study in a counterbalanced order. In all three parts, participants were required to pick up each of the four boxes separately in their own natural lifting technique. The order of the boxes that the participants were required to lift was randomized and command prompts were presented to the participants from a C# user interface displayed on a Microsoft Surface 50 inch display placed in front of them (illustrated in Figures 5.14a and 5.14b). Participants were required to follow the commands presented to them and perform the task described in 5.5.2.1. Their loading posture was monitored for ILP detection and application of correction feedback with respect to the modality and correction strategy.

### **Part 1: Audio feedback and self-correction**

When ILP was detected by the system based on the IMU sensor feedback, an audio notification in the form of distinct auditory tone was presented to the users, and the users were required to self-correct their ILP. In the case of torso inclination correction strategy, participants were required to correct their ILP by stabilizing their torso towards the ideal torso inclination angle until a second auditory tone indicating corrected posture (with ideal torso inclination and knee bend angles) was presented to the user. In the case of the knee bend correction strategy, participants were required to correct their ILP by bending their knees towards the ideal knee bend angles until a second auditory tone indicating corrected posture (with ideal torso inclination and knee bend angles) was presented to the user. The time between the two auditory notifications was recorded as response times for self-correcting ILP.

### **Part 2: Vibro-tactile feedback and self-correction**

When ILP was detected by the system based on the IMU sensor feedback, a haptic notification in the form of vibration was activated on IMU 1 placed on the torso, or IMU 2 and IMU 3 placed on the knees, and the users were required to self-correct their ILP. In the case of torso inclination correction strategy, participants were required to correct their ILP by stabilizing their torso towards the ideal torso inclination angle until the haptic vibration notification on IMU 1 stops, indicating restoration of proper loading posture (with ideal torso inclination and knee bend angles). In the case of knee bend correction strategy, participants were required to correct their ILP by bending their knees towards the ideal knee bend angles until the haptic vibration notification on IMU 2 and IMU 3 stops, indicating restoration of proper loading posture (with ideal torso inclination and knee bend angles) was presented to the user. The time between the activation and deactivation of the haptic notifications was recorded as response times for self-correcting ILP.

### **Part 3: EMS feedback and automatic correction**

When ILP was detected by the system, the EMS feedback was activated to apply the recorded EMS intensity to the rhomboid/hamstring muscles to invoke an involuntary muscle contraction in the torso inclination/knee bend correction strategy respectively.

In the case of torso inclination correction strategy, the rhomboid muscle contraction produces a pulling force in the opposite direction to torso inclination. This generates the physiological response of stabilizing the torso in to an upright position towards the ideal torso inclination angle for restoring proper loading posture. Figure 5.1 (A) & (B) illustrate the improper loading posture and Figure 5.1 (C) illustrates the corrected loading posture. The EMS was deactivated immediately when proper loading posture with the ideal torso inclination and knee bend angles have been achieved or restored. The response times for correcting the improper loading posture were recorded.

In the case of knee bend correction strategy, the hamstring muscle contraction produces a downward pulling force. This generates a physiological response of bending the knees towards the ideal knee bend angles restoring proper loading posture. Figure 5.1 (A) & (B) illustrate the improper loading posture and Figure 5.1 (C) illustrates the corrected loading posture. The EMS was deactivated immediately when proper loading posture with the ideal torso inclination and knee bend angles have been achieved or restored. The response times for correcting the improper loading posture were recorded. The results from the study are presented in section 5.6.2.

## 5.6 Results

### 5.6.1 Study 1

In the torso inclination correction strategy, the mean EMS intensity required for stabilizing the torso and correcting ILP was 40.34 mA ( $S.D = 8.6$  mA). In the knee bend correction strategy, the mean EMS intensity required for bending knees and correcting ILP was 36.7 mA ( $S.D = 7.5$  mA). To analyze the performance of our approach and to test the hypothesis in 5.4.3, we used repeated-measures 2-Factor ANOVA to determine the influence of feedback modality and correction strategy types on each dependent variable and the consolidated results are presented in Table 5.4, 5.5, 5.6, and 5.7. For the non-parametric user perception Likert scale data, we utilized the Aligned Rank Transform (ART) tool [203] and performed repeated measures 2-Factor ANOVA tests on the aligned ranks for the user perception Likert scale data.

#### 5.6.1.1 Average Correction Response Times

Average correction response times are calculated as a mean of the correction response times across all the four boxes for each modality for each participant. For H1, the main effect for feedback modality type yielded an  $F(2, 46) = 125.72$ ,  $p < 0.001$ , indicating a significant difference between Audio ( $M = 2.17$ ,  $S.D = 0.32$ ), Vibro-tactile ( $M = 1.75$ ,  $S.D = 0.41$ ), and EMS feedback modalities ( $M = 1.17$ ,  $S.D = 0.29$ ). A pairwise comparison between the three modalities indicated that EMS feedback modality delivered faster correction response times than both the audio and vibro-tactile modalities as illustrated in Figure 5.15a. The main effect for correction strategy type yielded an  $F(1, 23) = 0.087$ ,  $p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 1.69$ ,  $S.D = 0.56$ ), and knee bend correction strategies ( $M = 1.7$ ,  $S.D = 0.52$ ) as illustrated in Figure 5.15b. The interaction effect was not significant

$F(2, 46) = 0.294, p > 0.05$ . Significant differences were found in the system performance with regards to average correction response times between different feedback modalities with EMS feedback delivering the fastest correction. As a result, we were able to accept H1.

Table 5.4: 2-Factor ANOVA: Average Correction response times (ACRT). FM: Feedback Modality, CS: Correction Strategy.

Source	ACRT	p
FM	$F(2, 46) = 125.72$	$< 0.001^*$
CS	$F(1, 23) = 0.087$	0.77
FM X CS	$F(2, 46) = 0.294$	0.75

Note: \* indicates significant difference  $p < 0.05$ .

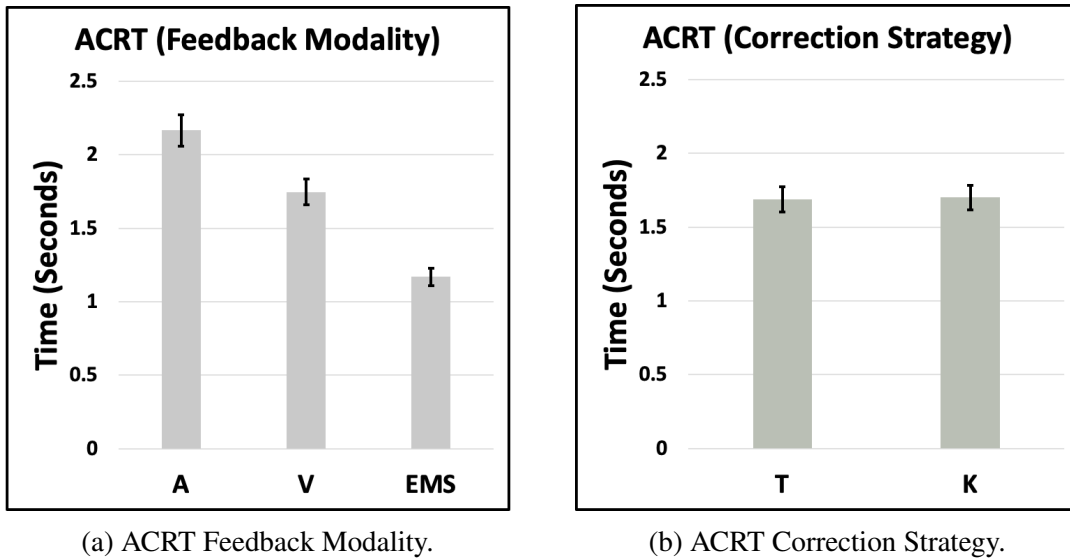


Figure 5.15: Average correction response times (ACRT) across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.1.2 User Perception of Correction Feedback Accuracy

For H2, the main effect for feedback modality type yielded an  $F(2, 46) = 5.56, p < 0.01$ , indicating a significant difference between Audio ( $M = 5.88, S.D = 1.23$ ), Vibro-tactile ( $M = 6.04, S.D = 1.44$ ), and EMS feedback modalities ( $M = 6.54, S.D = 0.74$ ) as illustrated in Figure 5.16a. A pairwise comparison of the means showed significant differences between the audio and vibro-tactile, and audio and EMS feedback types but no evidence of significant differences between the vibro-tactile and EMS feedback. The participants perceived EMS feedback to be more accurate than the audio, but not vibro-tactile feedback and hence we were not able to accept H2. The main effect for correction strategy type yielded an  $F(1, 23) = 3.09, p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 6.28, S.D = 1.02$ ), and knee bend correction strategies ( $M = 6.03, S.D = 1.32$ ) as illustrated in Figure 5.16b. The interaction effect was not significant  $F(2, 46) = 2.22, p > 0.05$ .

Table 5.5: 2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). FM: Feedback Modality, CS: Correction Strategy.

Source	CFA	p
FM	$F(2, 46) = 5.56$	$< 0.01^*$
CS	$F(1, 23) = 3.09$	0.09
FM X CS	$F(2, 46) = 2.22$	0.12

Note: \* indicates significant difference  $p < 0.05$ .

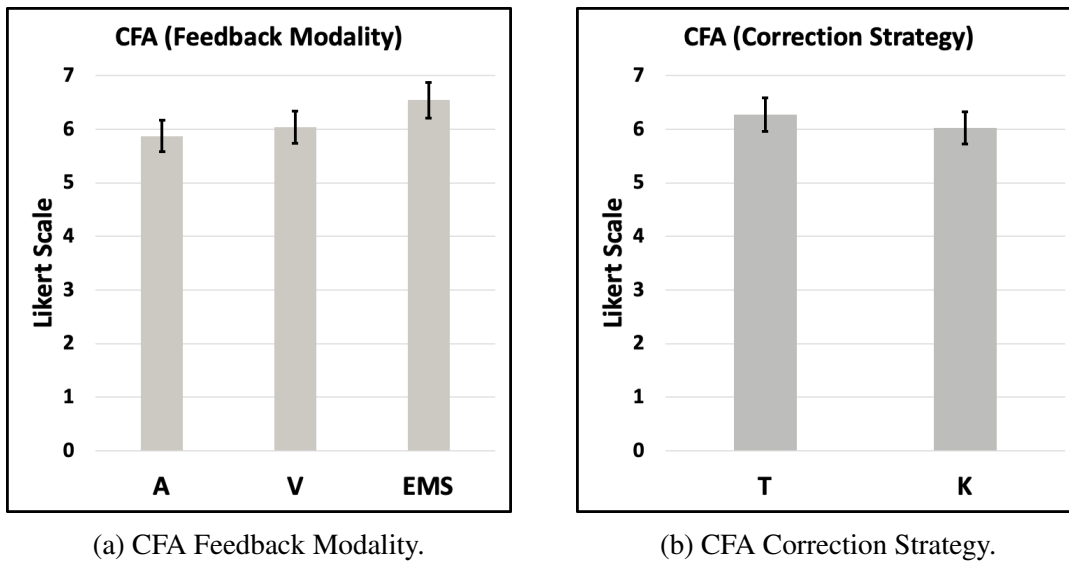


Figure 5.16: User perception of correction feedback accuracy across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.1.3 User Perception of Comfort

For H3, the main effect for feedback modality type yielded an  $F(2, 46) = 2.53$ ,  $p > 0.05$ , indicating no significant difference between Audio ( $M = 6.13$ ,  $S.D = 1.16$ ), Vibro-tactile ( $M = 6$ ,  $S.D = 1.48$ ), and EMS feedback modalities ( $M = 5.6$ ,  $S.D = 1.62$ ) as illustrated in Figure 5.17a. The main effect for correction strategy type yielded an  $F(1, 23) = 1.96$ ,  $p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 5.84$ ,  $S.D = 1.5$ ), and knee bend correction strategies ( $M = 5.98$ ,  $S.D = 1.39$ ) as illustrated in Figure 5.17b. The interaction effect was also not significant  $F(2, 46) = 0.71$ ,  $p > 0.05$ . As no significant differences were found in the main effects for modality or the correction strategy type, neither modality nor correction strategy had any influence on the user comfort. All three feedback modalities across both correction strategies delivered an equally comfortable user experience. As a result, we accept H3.

Table 5.6: 2-Factor ANOVA: User perception-Comfort. FM: Feedback Modality, CS: Correction Strategy.

Source	Comfort	p
FM	$F(2, 46) = 2.53$	0.09
CS	$F(1, 23) = 1.96$	0.18
FM X CS	$F(2, 46) = 0.71$	0.5

Note: \* indicates significant difference  $p < 0.05$ .

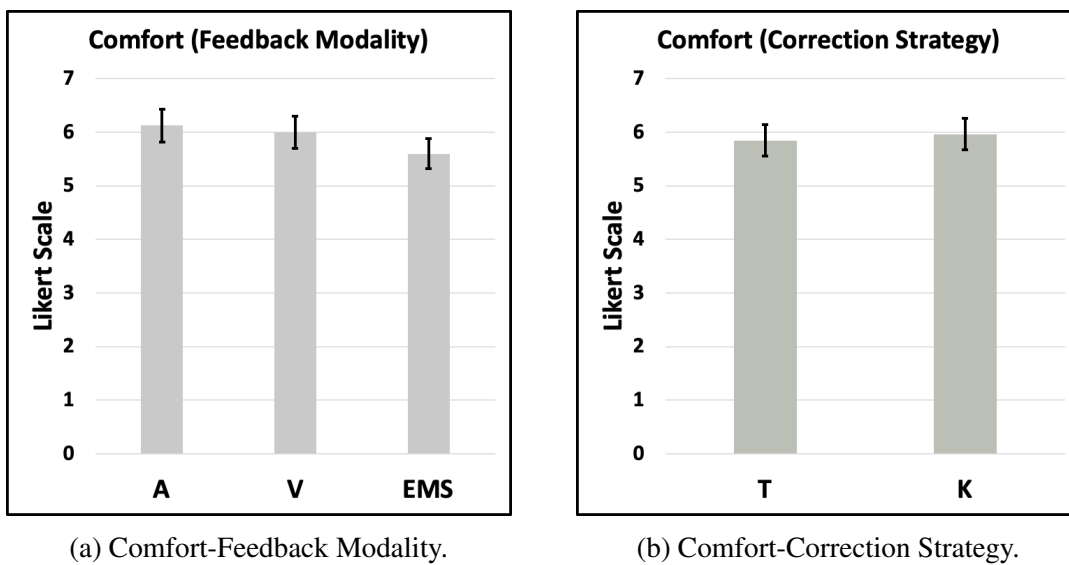


Figure 5.17: User perception of Comfort across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.



#### 5.6.1.4 User Perception of Task Disruption

For H4, the main effect for feedback modality type yielded an  $F(2, 46) = 2.68, p > 0.05$ , indicating no significant difference between Audio ( $M = 2.34, S.D = 1.83$ ), Vibro-tactile ( $M = 1.97, S.D = 1.67$ ), and EMS modalities ( $M = 2.31, S.D = 1.46$ ) as illustrated in Figure 5.18a. The main effect for correction strategy type yielded an  $F(1, 23) = 0.69, p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 2.4, S.D = 1.86$ ), and knee bend correction strategies ( $M = 2.03, S.D = 1.42$ ) as illustrated in Figure 5.18b. The interaction effect was also not significant  $F(2, 46) = 0.19, p > 0.05$ . As no significant differences were found in the main effects for feedback modality or the correction strategy type, neither feedback modality nor correction strategy had any influence on task disruption. All three feedback modalities across the two correction strategies disrupted the participants task equally. As a result, we accept H4.

Table 5.7: 2-Factor ANOVA: User Perception-Task disruption (TD). FM: Feedback Modality, CS: Correction Strategy.

Source	TD	p
FM	$F(2, 46) = 2.68$	0.12
CS	$F(1, 23) = 0.69$	0.51
FM X CS	$F(2, 46) = 0.19$	0.83

Note: \* indicates significant difference  $p < 0.05$ .

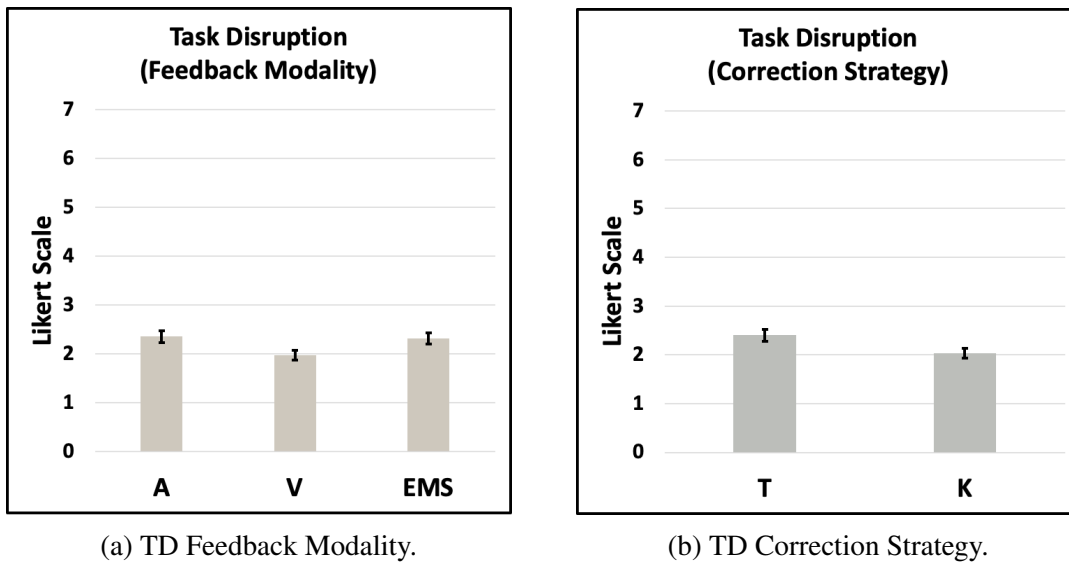


Figure 5.18: User perception of Task Disruption across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.1.5 User Perception and Preferences

Mean rankings for user perception of correction feedback accuracy, ILP correction assistance, comfort, and task disruption are shown in Figure 5.19. Participants ranked their ILP correction assistance on a 7-point scale where 1 means not at all, and 7 means completely assisted to restore proper lifting posture. Participants' ranking indicated that EMS feedback modality delivered best ILP correction assistance ( $M = 6.02, S.D = 1.36$ ), followed by the vibro-tactile feedback ( $M = 5.6, S.D = 1.36$ ), and audio feedback delivered lowest ( $M = 5.04, S.D = 1.74$ ). Additionally, the participants' ranking of ILP correction assistance across the two correction strategies indicated that both torso inclination ( $M = 5.58, S.D = 1.4$ ), and knee bend correction strategies ( $M = 5.53, S.D = 1.68$ ) delivered equally good assistance in correcting ILP.

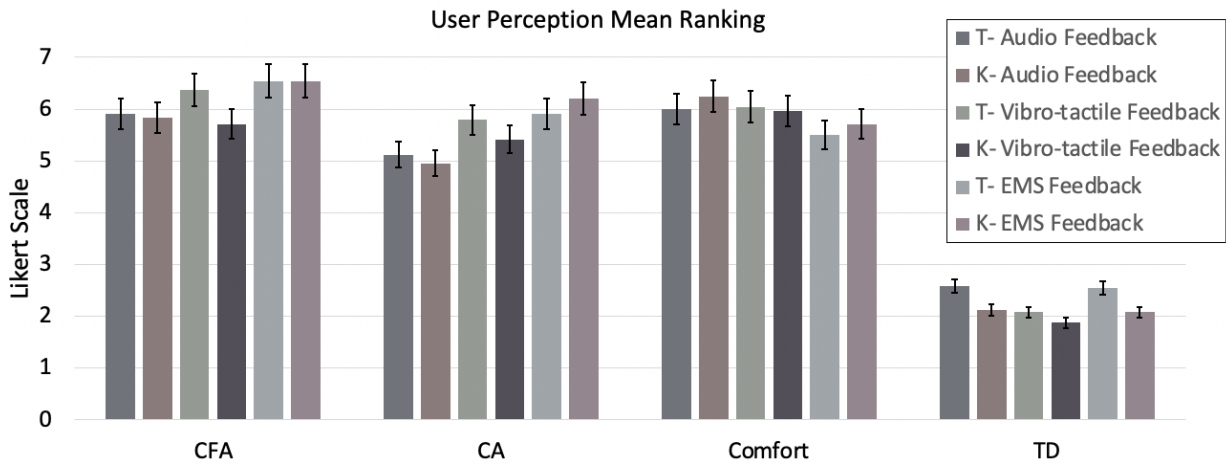


Figure 5.19: User perception mean rankings for correction feedback accuracy (CFA), ILP correction assistance (CA), comfort, and task disruption (TD) across all feedback modalities and correction strategy types. Likert Scale: 1-meaning not at all, 7-meaning completely. T: Torso inclination correction strategy, K: Knee bend correction strategy. Error bars: 95% CI.

Further, when participants were asked about their preferred feedback modality for correcting ILP, 54% of the study population reported that EMS feedback was their preferred correction feedback technique, while 25% preferred the vibro-tactile feedback, and 21% preferred the audio feedback Figure 5.20a. When participants were asked about their preferred correction strategy, 67% of the study population preferred torso inclination correction strategy while 33% preferred the knee bend correction strategy Figure 5.20b. However, 17 out of 24 participants reported that they would be willing to purchase an EMS feedback based ILP posture correction device if it were a commercially available product. Participants also ranked their shared responsibility with auto-correction utilizing EMS on a 7-point scale where 1 means not at all and 7 means completely. The mean shared responsibility exhibited by the participants was 2.16 ( $S.D = 0.99$ ) in the torso inclination correction strategy and 2.5 ( $S.D = 0.86$ ) in the knee bend correction strategy. Participants ranked EMS feedback modality to be a highly interesting concept for automatic ILP correction on a 7-point Likert scale with a mean ranking of 6.67 ( $S.D = 0.84$ ) for torso inclination correction strategy, and

a mean ranking of 6.33 ( $S.D = 1.14$ ) for knee bend correction strategy.

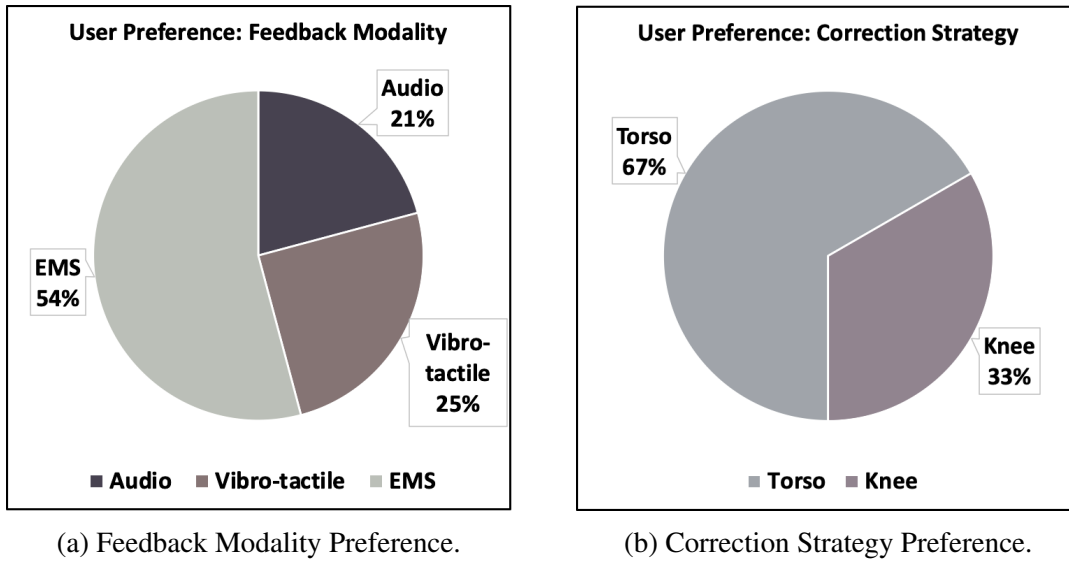


Figure 5.20: User preference of (a) Feedback Modality, & (b) Correction Strategy.

### 5.6.2 Study 2

For the torso inclination correction strategy, the mean EMS intensity required for stabilizing the torso and correcting ILP was  $43.3 \text{ mA}$  ( $S.D = 7.3 \text{ mA}$ ). For the knee bend correction strategy, the mean EMS intensity required for bending knees and correcting ILP was  $35.8 \text{ mA}$  ( $S.D = 6.5 \text{ mA}$ ). To analyze the performance of our approach and to test the hypothesis in 5.5.3, we used repeated-measures 2-Factor *ANOVA* to determine the influence of feedback modality and correction strategies types on each dependent variable and the consolidated results are presented in Table 5.8, 5.9, 5.10, and 5.11. For the non-parametric user perception Likert scale data, we utilized the Aligned Rank Transform (ART) tool [203] and performed repeated measures 2-Factor *ANOVA* tests on the aligned ranks for the user perception Likert scale data.

### 5.6.2.1 Average Correction Response Times

Average correction response times are calculated as a mean of the correction response times across all the four boxes for each modality for each participant. For H1, the main effect for feedback modality type yielded an  $F(2, 60) = 24.69$ ,  $p < 0.001$ , indicating a significant difference between Audio ( $M = 1.43$ ,  $S.D = 0.52$ ), Vibro-tactile ( $M = 1.17$ ,  $S.D = 0.38$ ), and EMS feedback modalities ( $M = 0.71$ ,  $S.D = 0.27$ ). A pairwise comparison between the three modalities indicated that EMS feedback modality delivered faster correction response times than both the audio and vibro-tactile feedback modalities illustrated in Figure 5.21a. The main effect for correction strategy type yielded an  $F(1, 30) = 0.20$ ,  $p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 1.08$ ,  $S.D = 0.57$ ), and knee bend correction strategies ( $M = 1.12$ ,  $S.D = 0.48$ ) as illustrated in Figure 5.21b. The interaction effect was not significant  $F(2, 60) = 5.80$ ,  $p > 0.05$ . Significant differences were found in the system performance with regards to average correction response times between the different feedback modalities with the EMS feedback delivering the fastest correction. As a result, we were able to accept H1.

Table 5.8: 2-Factor ANOVA: Average Correction response times (ACRT). FM: Feedback Modality, CS: Correction Strategy.

Source	ACRT	p
FM	$F(2, 60) = 24.69$	$< 0.001^*$
CS	$F(1, 30) = 0.20$	0.66
FM X CS	$F(2, 60) = 5.80$	0.096

Note: \* indicates significant difference  $p < 0.05$ .

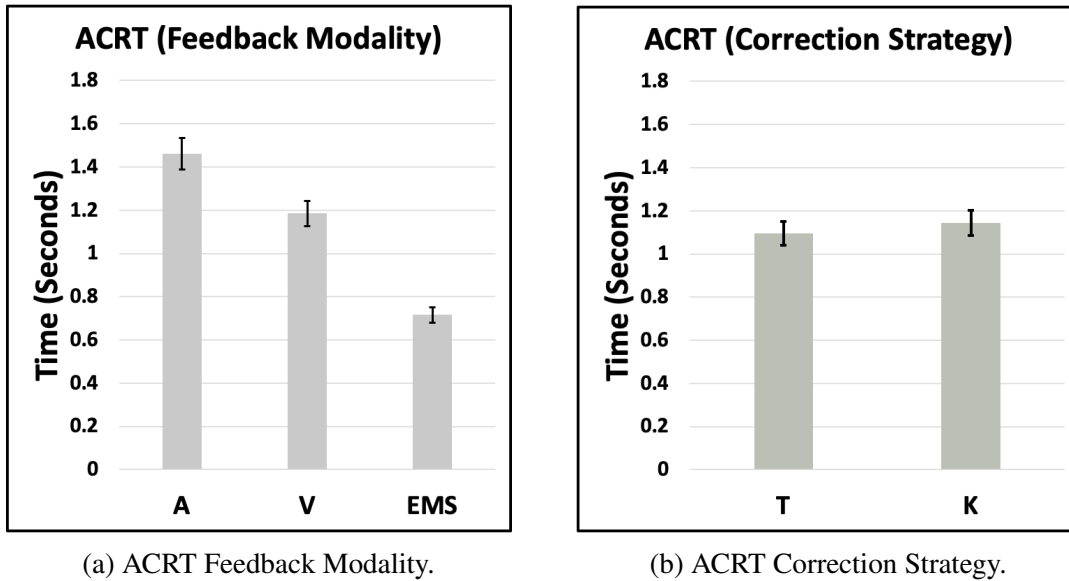


Figure 5.21: Average correction response times (ACRT) across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V:Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.2.2 User Perception of Correction Feedback Accuracy

For H2, the main effect for feedback modality type yielded an  $F(2, 68) = 11.32, p < 0.01$ , indicating a significant difference between Audio ( $M = 5.14, S.D = 1.36$ ), Vibro-tactile ( $M = 5.92, S.D = 0.81$ ), and EMS feedback modalities ( $M = 6.08, S.D = 0.84$ ) as illustrated in Figure 5.22a. A pairwise comparison of the means showed significant differences between the audio and vibro-tactile, and audio and EMS feedback types but no evidence of significant differences between the vibro-tactile and EMS feedback. The participants perceived EMS feedback to be more accurate than the audio, but not vibro-tactile feedback and hence we were not able to accept H2. The main effect for correction strategy type yielded an  $F(1, 34) = 0.15, p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 5.67, S.D = 1.18$ ),

and knee bend correction strategies ( $M = 5.76, S.D = 1.03$ ) as illustrated in Figure 5.22b. The interaction effect was not significant  $F(2, 68) = 1.7, p > 0.05$ .

Table 5.9: 2-Factor ANOVA: User Perception-Correction feedback accuracy (CFA). FM: Feedback Modality, CS: Correction Strategy.

Source	CFA	p
FM	$F(2, 68) = 11.32$	$< 0.001^*$
CS	$F(1, 34) = 0.15$	0.71
FM X CS	$F(2, 68) = 1.70$	0.19

Note: \* indicates significant difference  $p < 0.05$ .

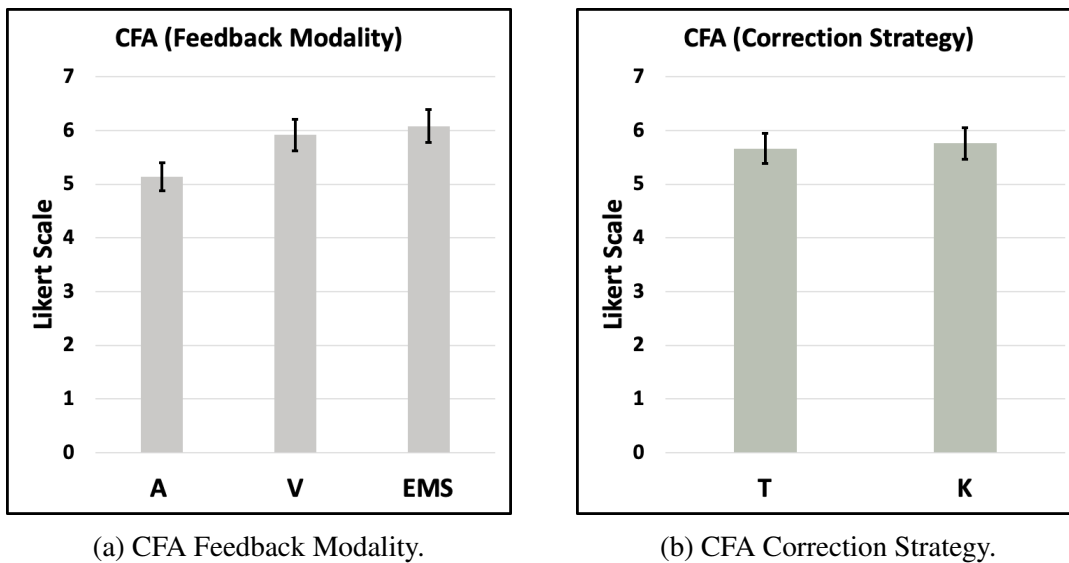


Figure 5.22: User perception of correction feedback accuracy across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.2.3 User Perception of Comfort

For H3, the main effect for feedback modality type yielded an  $F(2, 68) = 0.67, p > 0.05$ , indicating no significant difference between Audio ( $M = 5.81, S.D = 1.35$ ), Vibro-tactile ( $M = 6.03, S.D = 0.99$ ), and EMS feedback modalities ( $M = 5.75, S.D = 1.05$ ) as illustrated in Figure 5.23a. The main effect for correction strategy type yielded an  $F(1, 34) = 0.14, p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 5.91, S.D = 1.2$ ), and knee bend correction strategies ( $M = 5.81, S.D = 1.08$ ) as illustrated in Figure 5.23b. The interaction effect was also not significant  $F(2, 68) = 0.5, p > 0.05$ . As no significant differences were found in the main effects for modality or the correction strategy type, neither modality nor correction strategy had any influence on the user comfort. All three feedback modalities across both correction strategies delivered an equally comfortable user experience. As a result, we accept H3.

Table 5.10: 2-Factor ANOVA: User perception-Comfort. FM: Feedback Modality, CS: Correction Strategy.

Source	Comfort	p
FM	$F(2, 68) = 0.67$	0.52
CS	$F(1, 34) = 0.14$	0.71
FM X CS	$F(2, 68) = 0.5$	0.66

Note: \* indicates significant difference  $p < 0.05$ .



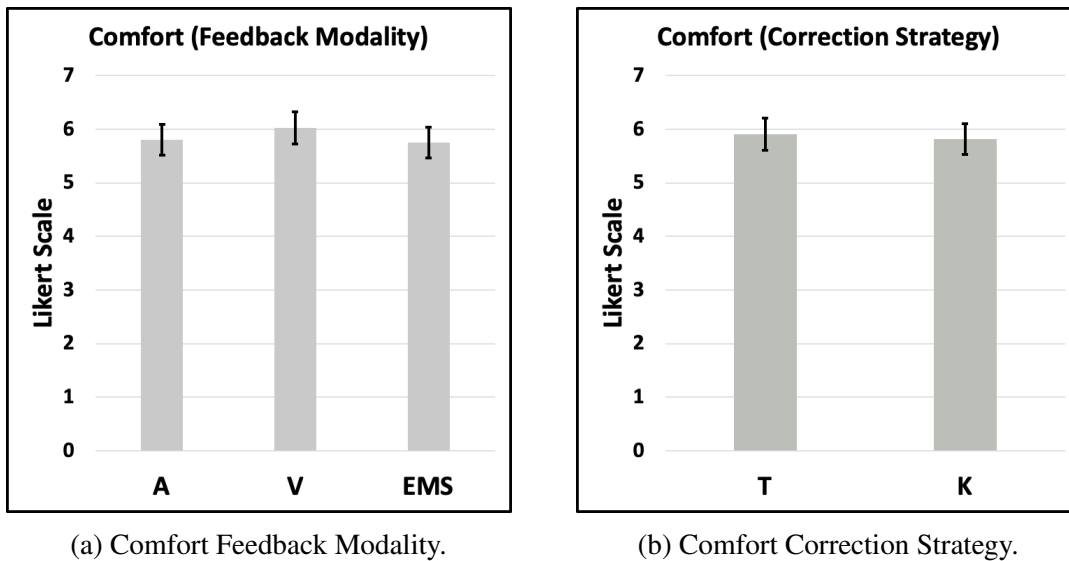


Figure 5.23: User perception of Comfort across ((a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

#### 5.6.2.4 User Perception of Task Disruption

For H4, the main effect for feedback modality type yielded an  $F(2, 68) = 0.68$ ,  $p > 0.05$ , indicating no significant difference between Audio ( $M = 2.58$ ,  $S.D = 2$ ), Vibro-tactile ( $M = 2.25$ ,  $S.D = 1.40$ ), and EMS modalities ( $M = 2.44$ ,  $S.D = 1.18$ ) as illustrated in Figure 5.24a. The main effect for correction strategy type yielded an  $F(1, 34) = 0.07$ ,  $p > 0.05$ , indicating that the effect of correction strategy type was not significant between torso inclination ( $M = 2.37$ ,  $S.D = 1.63$ ), and knee bend correction strategies ( $M = 2.48$ ,  $S.D = 1.50$ ) as illustrated in Figure 5.24b. The interaction effect was also not significant  $F(2, 68) = 0.39$ ,  $p > 0.05$ . As no significant differences were found in the main effects for feedback modality or the correction strategy type, neither feedback modality nor correction strategy had any influence on task disruption. All three feedback modalities across the two correction strategies disrupted the participants task equally. As a result, we accept H4.

Table 5.11: 2-Factor ANOVA: User Perception-Task disruption (TD). FM: Feedback Modality, CS: Correction Strategy.

Source	TD	p
FM	$F(2, 68) = 0.68$	0.51
CS	$F(1, 34) = 0.07$	0.79
FM X CS	$F(2, 68) = 0.39$	0.68

Note: \* indicates significant difference  $p < 0.05$ .

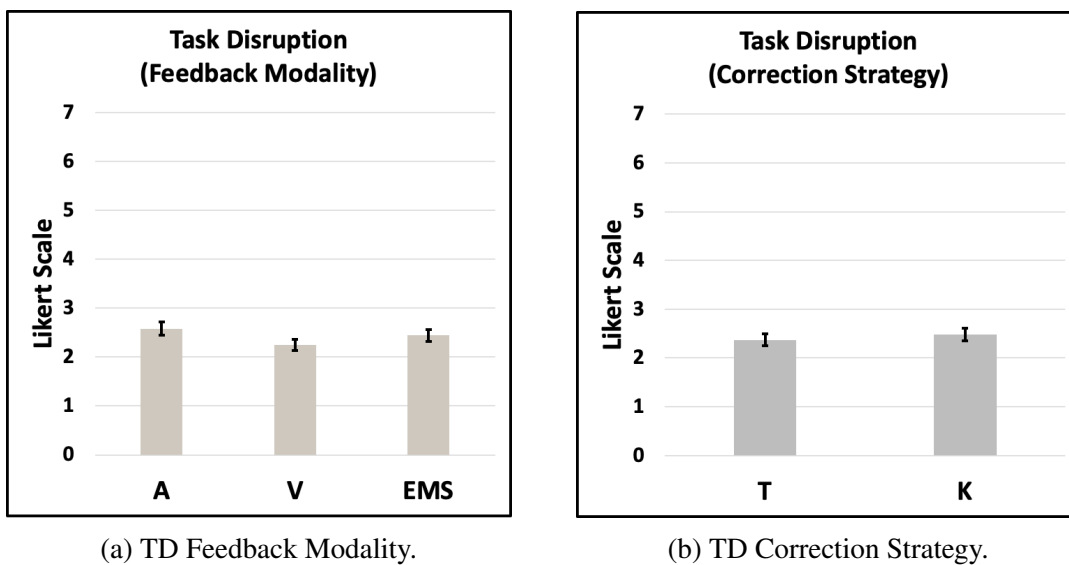


Figure 5.24: User perception of Task Disruption across (a) Feedback Modality, & (b) Correction Strategy. Error bars: 95% CI. A: Audio, V: Vibro-tactile, T: Torso Inclination Correction Strategy, K: Knee Bend Correction Strategy.

### 5.6.2.5 User Perception and Preferences

Participants ranked their ILP correction assistance on a 7-point scale where 1 means not at all, and 7 means completely assisted to restore proper lifting posture. Participants' ranking indicated that EMS feedback modality delivered best ILP correction assistance ( $M = 6.17, S.D = 0.97$ ), followed by the vibro-tactile feedback ( $M = 5.86, S.D = 1.09$ ), and audio feedback delivered lowest ( $M = 4.67, S.D = 1.41$ ). Additionally, the participants' ranking of ILP correction assistance across the two correction strategies indicated that both torso inclination ( $M = 5.89, S.D = 1.28$ ), and knee bend correction strategies ( $M = 5.54, S.D = 1.32$ ) delivered equally good assistance in correcting ILP.

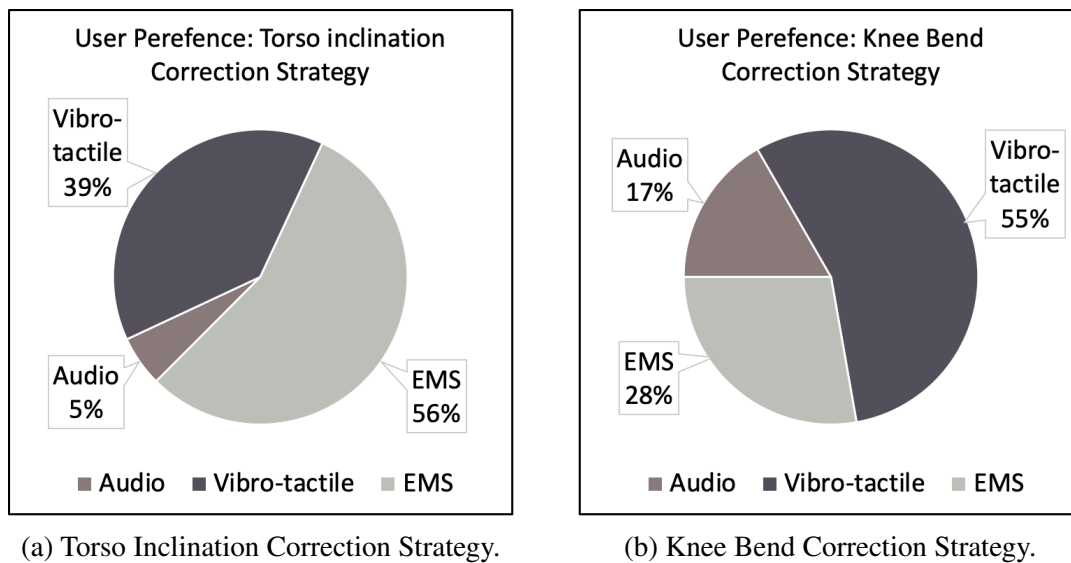


Figure 5.25: User preference of feedback modality in (a) Torso inclination correction strategy & (b) Knee bend correction strategy.

Further, when participants were asked about their preferred feedback modality for correcting ILP in the torso inclination correction strategy, 56% of the study population reported that EMS feedback was their preferred correction feedback technique, while 39% preferred the vibro-tactile feedback,

and 5% preferred the audio feedback (illustrated in 5.25a). When participants were asked about their preferred feedback modality for correcting ILP in the knee bend correction strategy, 28% of the study population reported that EMS feedback was their preferred correction feedback technique, while 55% preferred the vibro-tactile feedback, and 17% preferred the audio feedback (illustrated in 5.25b). However, 14 out of 18 participants in the torso inclination correction strategy type reported that they would be willing to purchase an EMS feedback with torso inclination correction strategy for ILP posture correction if it were a commercially available product, and 12 out of 18 participants in the knee bend correction strategy type reported that they would be willing to purchase an EMS feedback with knee bend correction strategy for ILP posture correction if it were a commercially available product. Participants also ranked their shared responsibility with auto-correction utilizing EMS on a 7-point scale where 1 means not at all and 7 means completely. The mean shared responsibility exhibited by the participants was 2.25 ( $S.D = 1.36$ ). Participants ranked EMS feedback modality to be a highly interesting concept for automatic ILP correction with a mean ranking of 6.71 ( $S.D = 0.46$ ) on a 7-point Likert scale.

## 5.7 Discussion

Although previous research on ILP detection and alert mechanisms has been conducted, feedback responsiveness and user experience with the feedback mechanisms have not been measured or reported. As a result, we conducted two studies to compare our automatic ILP detection and correction approach against traditional audio and vibrotactile feedback systems. Our studies mainly focussed on the evaluation of system performance and user perception of our automatic ILP detection and correction system against the alternative feedback systems.

The correction response times were measured as the time between the activation and deactivation of the feedback after ILP was detected and corrected respectively. Average correction response times

were calculated from the mean of the correction response times to ILP across all the boxes. Across both correction strategies, our automatic correction with EMS feedback delivered the fastest ILP correction with an average correction response time of 1.17 *Seconds* in Study 1, and 0.71 *Seconds* in Study 2 (illustrated in Figure 5.26a), while the vibro-tactile feedback delivered significantly slower corrections at 1.75 *Seconds*, and 1.17 *Seconds* for Study 1, and Study 2 respectively. The audio feedback was the slowest at delivering corrections at 2.17 *Seconds*, and 1.43 *Seconds* for Study 1, and Study 2 respectively. As a result, H1 was accepted across both the studies. The EMS feedback was fastest due the fact that the correction was automatically affected with out any effort from the participant, while the audio, and vibro-tactile feedbacks placed a cognitive load on the user to asses their torso and knee bend posture while being engaged in the process of performing the lifting tasks. This cognitive load on the user to understand the received feedback, assess the current torso inclination, and knee bend angles, and making a conscious effort to self-correct the ILP resulted in additional correction time. Alternatively, both torso inclination correction strategy and knee bend correction strategy across all three modalities delivered equally fast ILP corrections at 1.68 *Seconds*, and 1.7 *Seconds* respectively in Study 1 and 1.09 *Seconds*, and 1.14 *Seconds* for torso inclination correction strategy and knee bend correction strategy respectively in Study 2 indicating no significant differences between the two correction strategies (illustrated in Figure 5.26b). Due to the dynamic nature of the ILP, and being one of the leading risk factors of lower back pain, faster corrections through EMS would prove to be crucial in preventing the onset of a long term RSI, and reinforce healthy posture for better lifting techniques.

It was interesting to note the significant differences in the correction response times across the two studies for all feedback modalities and across both correction strategies. This can be attributed primarily to the nature of the two studies, the range of motion of the torso and knees in the correction strategies across the studies and learning effects. In Study 1, participants emulated ILP with bent over posture resulting in higher torso inclination angles and lower knee bend angles which required

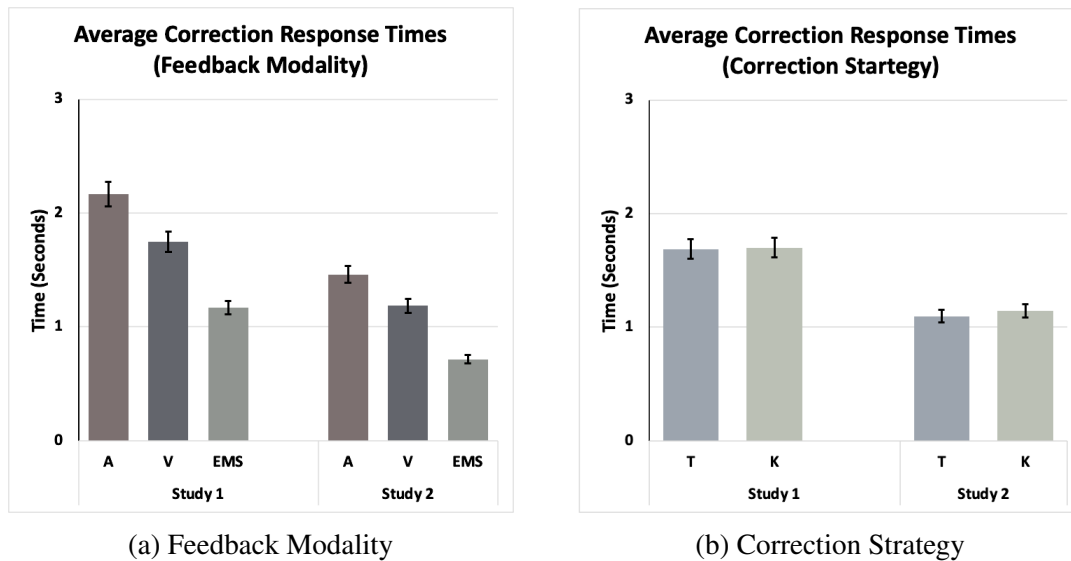


Figure 5.26: Average Correction Response Times of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile feedbacks. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI.

slightly more correction time to stabilize the torso and bend the knees, while in study 2, participants performed the tasks in a more ecologically valid manner where the participants were free to perform the lifting task in their natural way. Additionally, Study 1 required participants to perform ILP during each lift while Study 2 had no such requirements which allowed participants to consciously or subconsciously learn and improve their posture as they go about completing the lifting tasks. The learning effects of the first ILP correction received by the participants enabled them to re-assess their lifting posture and improve their posture with lower torso inclination and greater knee bend. This in turn required lesser range of motion for corrections to stabilize the torso and bend knees in the subsequent lifts they performed. The results also indicate that EMS would be capable of delivering faster ILP corrections across different boxes of different sizes and loads, and makes it especially advantageous to be developed as a smart wearable intervention device for manual workers in construction, factories, and shipping, who handle a range of loads in different sizes everyday.

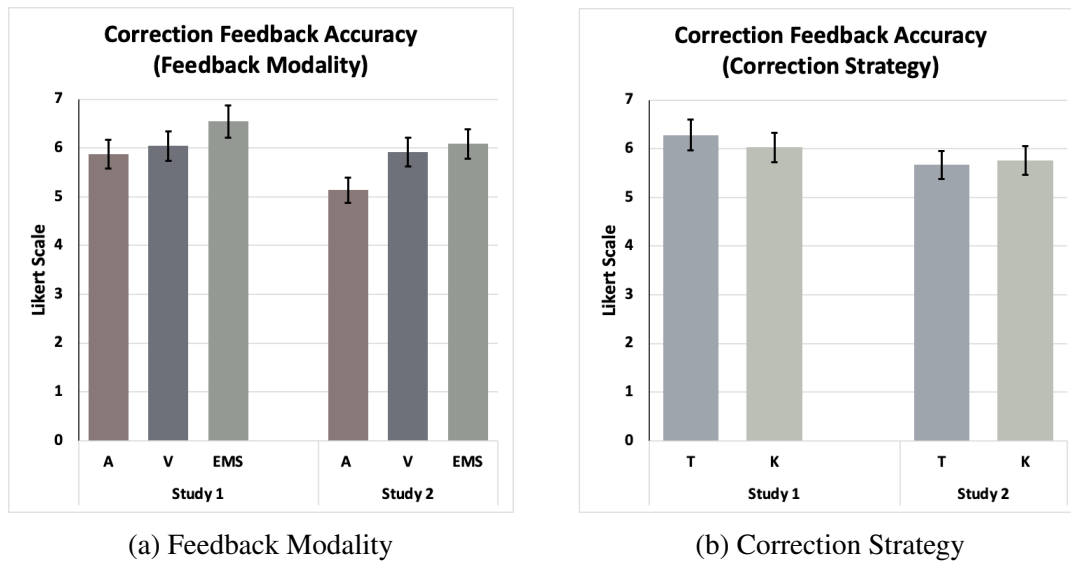


Figure 5.27: Mean User Ranking for Correction Feedback Accuracy of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI.

Participants ranked their perception of the correction feedback accuracy across all modalities and correction strategies. In both studies, the EMS and the vibro-tactile feedbacks were perceived to be highly accurate, while the audio feedback was perceived to be the least accurate among the three modalities (illustrated in Figure 5.27a). As a result, H2 was not accepted across both studies. Additionally, participants perceived both correction strategies to be equally highly accurate with mean rankings of 6.27 and 6.02 for torso inclination and knee bend correction strategies respectively in Study 1, and 5.67 and 5.76 for torso inclination and knee bend correction strategies respectively in Study 2 (illustrated in Figure 5.27b). The high rankings for the EMS and vibro-tactile feedbacks may be due to the distinct somatosensory confirmation offered through the activation and deactivation of vibrotactile and EMS feedbacks allowing the user to better respond to feedback.

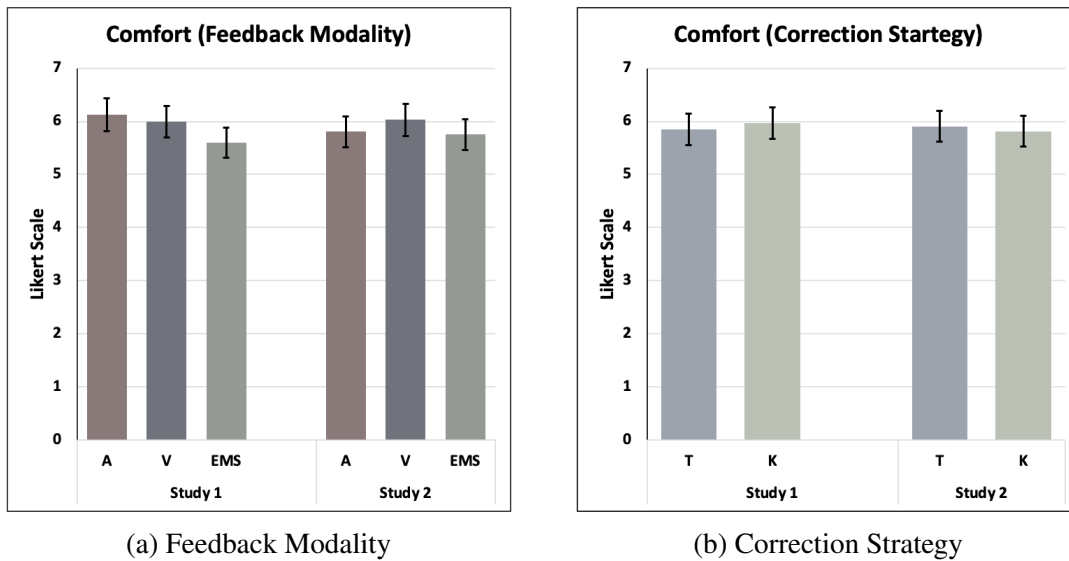


Figure 5.28: Mean User Ranking for Comfort of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI.

Participants ranked their comfort and disruption across the three modalities and the two correction strategies across the two studies as illustrated in Figures 5.28a, 5.28b, 5.29a, 5.29b. In both Studies, neither the feedback modality nor the correction strategy had any influence on the user comfort or task disruption. In comparison to the audio and vibro-tactile feedback types, EMS feedback produces a stronger somatosensory effect through its involuntary muscular contractions. However, participants ranked all three modalities equally comfortable and equally disruptive. As a result, we accepted H3 and H4 in both studies. Careful EMS calibration played an important role in achieving the desired ILP correction in both torso inclination and knee bend correction strategies with an acceptable level of comfort and disruption similar to the comfort and disruption delivered in the audio and vibro-tactile feedback mechanisms. The participants' rankings showing similar level of comfort and disruption across the feedback modalities and correction strategies indicating an acceptance of EMS feedback as a potentially equal alternative to the traditional feedback systems



along with an additional benefit of automatic ILP correction.

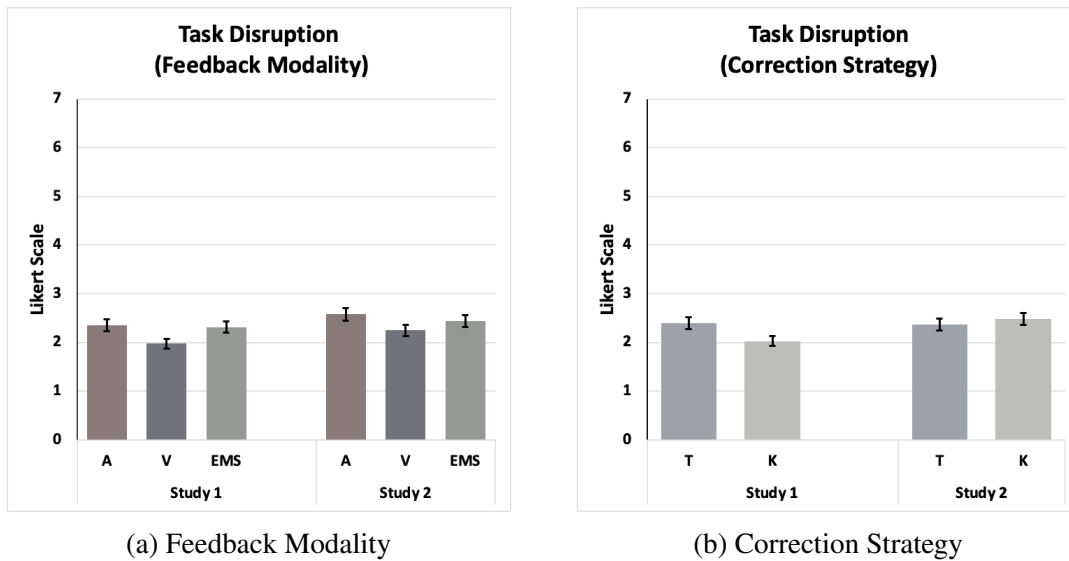


Figure 5.29: Mean User Ranking for Task Disruption of the different modalities and correction strategies across Study 1 and Study 2. A: Audio, V: Vibro-tactile. T: Torso Inclination Correction, K: Knee Bend Correction strategies. Error bars: 95% CI.

Participants' ranking of their ILP correction assistance during the two correction strategies indicated that EMS feedback delivered the best correction assistance followed by the vibro-tactile feedback, and audio feedback offered the worst correction assistance. Both the torso inclination and knee bend strategies offered an equally good correction assistance. This may be due to the fact that both strategies are linked towards delivering ideal lifting angles for the torso inclination and knee bend. This finding illustrates the fact that participants perceived both EMS feedback based correction strategies as a potential alternative intervention technique to correct ILP. This also presents an opportunity to develop a smart wearable ILP intervention device that delivers a fast and discrete feedback capable of correcting ILP. Also, this would make EMS-based smart intervention wearable technology accessible for use especially by manual laborers and construction workers who are involved with handling procurement and shipment of boxes of different sizes and loads.

Across the two studies, the EMS intensity required for effecting torso correction, and knee bend were approximately 43 *mA*, and 36 *mA* respectively. The torso correction EMS intensity was similar to the torso stabilization EMS intensity in case of correcting slouching [95]. The EMS intensity for knee bend correction was slightly lower than the torso correction. This may be due to the fact that the rhomboid muscles in the torso are more active and relatively less sensitive to EMS than the less active and more sensitive hamstring muscles. Participants also reported their shared responsibility in helping/aiding the automatic ILP correction process in the EMS feedback mechanism. This indicates the learning effects of ILP detection and correction on the participants, and their willingness to get involved in the correction process for achieving better posture control while lifting. Further, it also demonstrates that EMS feedback with its somatosensory feedback encouraged the participants to get involved in the correction process.

In conclusion, we have demonstrated that our physiological feedback loop based on automatic ILP detection and correction with EMS is a viable approach to supporting ILP correction while stabilizing torso and knee bending towards ideal lifting angles to prevent risk of injury. Our auto-correction system utilizing EMS feedback demonstrated significantly faster ILP correction response times compared to the self-correction in the audio and vibro-tactile feedback. Our approach also showed that participants perceived EMS feedback to be highly accurate, equally comfortable, and produced no more disruption than the alternative techniques it was tested against in both the torso inclination and knee bend correction strategies. Therefore, our autonomous ILP detection and correction system utilizing EMS shows promising results and could be a useful alternative or inclusion to the existing environment, health, and safety (EHS) guidelines for mitigating risk of workplace injury, improving employee health, and preventive health care.

The next chapter presents a discussion on the results and scope of our automatic poor posture detection and correction systems for correcting slouching, AWD, and ILP.

## **CHAPTER 6: DISCUSSION**

With the recent advancements, and interest in EMS for interactive HCI applications, and EMS feedback for accelerating preemptive reflexes [93, 94, 153], we were interested in understanding the capabilities of EMS feedback in automatic poor posture correction across a range of activity levels from sedentary (slouching), moderate (AWD), and dynamic activity (ILP). In comparison to the alternative traditional feedback systems, we found several benefits to automatic posture correction using EMS feedback. Our automatic approach utilizing EMS feedback was able to achieve significantly faster correction at a high accuracy while delivering an equally comfortable user experience across the different posture problems, tested under varying levels of engagement, posture awareness, and activity levels. Even though research has been conducted on detecting poor posture and alerting users through traditional feedback systems, the system's correction responsiveness and user perception parameters have not been measured or reported. Therefore, our research primarily focused on evaluation of the system performance and user perception of our EMS feedback based automatic poor posture detection and correction technique against traditional audio, visual, and vibro-tactile feedback mechanisms requiring self correction by the user.

### **6.1 EMS Intensity**

Our research on automatic posture correction through involuntary muscular contractions relied primarily on the intensity of the EMS being applied to the different muscles for generating a corrective physiological response to effect posture correction and restoring and maintaining good posture. Table 6.1 illustrates the different muscles stimulated for correcting slouching, AWD and ILP, and the corresponding mean EMS intensity applied to the muscles to generate an involuntary muscular contraction. Torso stabilization for correcting slouching, and ILP (torso inclination

Table 6.1: Mean EMS Intensity utilized for stimulating different muscles for correcting poor posture

Poor Posture	Stimulated Muscle	Task	EMS Intensity (mA)
Slouching	Rhomboid	Text Entry	39.72
		Mobile Game	47.22
AWD	Tibialis	Quiet Standing	50.55
		Mobile Game	51.94
ILP	Rhomboid	Lifting Boxes	40.34
	Hamstring	Lifting Boxes	36.7

correction strategy) through the stimulation of the rhomboid muscle required approximately 39 mA to 47 mA, while ILP knee bending correction through hamstring muscle stimulation required approximately 36 mA, and counter-weight shifting for AWD correction through the tibialis muscle stimulation required approximately 50 mA to 52 mA. The different intensities required for correcting the different poor postures may be primarily due to the difference in muscle physiology, and their accessibility. The rhomboid, and the hamstring muscles are more accessible physiologically in comparison to the tibialis muscles which are regarded as a more deeper muscle group requiring higher EMS intensities for achieving muscular contractions. Additional factors may be the level of engagement during tasks, and the constraints to their range of movements while performing the tasks. It was interesting to note that EMS feedback was able to correct poor postures across range of activity levels from sedentary activity in the case of slouching correction, to moderate activity in AWD correction, and dynamic high activity in ILP correction. It was also interesting to note that the slouching correction in the text entry task and ILP torso inclination correction strategy required lesser EMS intensity to stabilize the torso in comparison to the slouching correction in the mobile game task. This may be due to the level of engagement in the mobile game task, and the constraints it places on the users' torso while being tethered to a smart phone device, and a highly engaging game.

## 6.2 Correction Response Times

The correction response times were measured as the time between the activation and deactivation of the feedback after poor posture was detected, and proper posture was restored respectively. The results from our studies indicated that EMS delivered the fastest posture correction across all three poor postures (illustrated in Figure 6.1) that were studied, with a mean correction response time of 2.79 *Seconds* for slouching correction, 1.32 *Seconds* for AWD correction, and 0.92 *Seconds*, and 0.99 seconds for ILP correction in the torso inclination correction strategy and knee bend correction strategy respectively. Our EMS based automatic approach also outperformed the traditional audio, visual, vibrotactile feedback systems across different tasks with varying levels of engagement and activity levels. It was interesting to note that the correction response times for EMS feedback are greater for slouching posture correction, and fastest for ILP correction. This indicates that EMS feedback correction in sedentary slouched posture takes longer to correct in comparison to the dynamic high activity ILP correction.

It was interesting to note that the correction response times for EMS feedback decrease with increased activity level (illustrated in the Figure 6.1) with sedentary slouched posture correction being the slowest to dynamic high activity ILP correction being the fastest, and moderate activity AWD correction in between. This may be due to the fact that the sedentary slouched posture places constraints on the range of lumbar motion which in turn affects the speed of torso stabilization. Alternatively, the ILP being a more dynamic poor posture places no physical constraints on the torso stabilization prior to the lift phase, and thereby allows for faster torso stabilization and correction. To summarize, our automatic approach using EMS feedback was approximately 43% faster than the visual feedback, 44% faster than the audio feedback, and 33% faster than the vibro-tactile feedback. Finally, the speed of posture correction can be increased with higher EMS intensities, however, this may negatively affect the user experience with respect to comfort and disruption. As a result, an

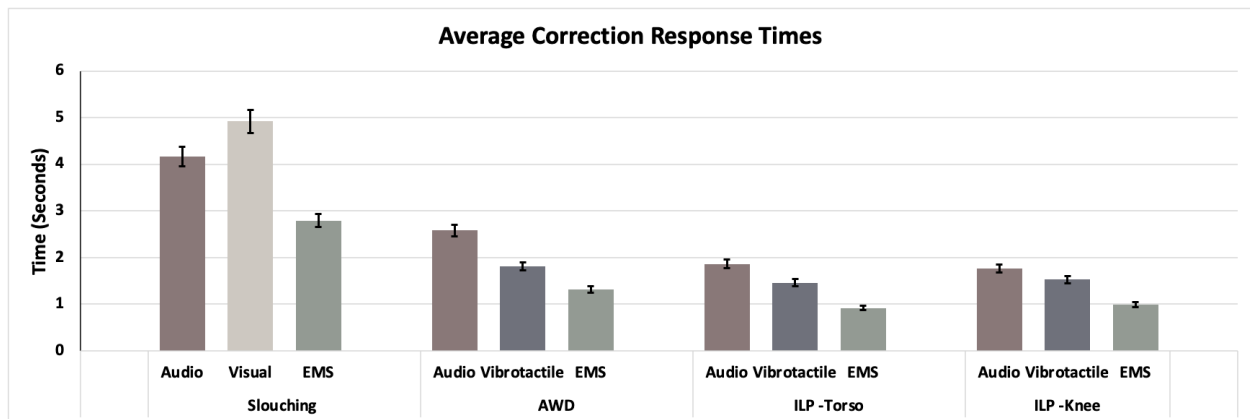


Figure 6.1: Average correction response times for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities. Error bars: 95% CI.

optimal trade off between the speed of correction, and user experience may be achieved through careful calibration of the EMS intensity required for affecting posture correction, and being as comfortable as possible at the same time. The speed and effectiveness of posture correction plays a crucial role in reinforcing healthy posture, and preventing poor postural habits that may result in RSI and eventually long term health conditions that affect productivity.

### 6.3 Accuracy of Correction Feedback

The perceived accuracy of correction feedback played an important role in determining users perceived level of confidence in our EMS based automatic approach, and to establish EMS feedback as a viable alternative to traditional feedback mechanisms. From our studies, it was evident that the accuracy of correction feedback for EMS feedback was perceived to be more accurate than the audio and visual feedbacks, and equally accurate in comparison to the vibro-tactile feedback (illustrated in Figure 6.2). This may be due to the fact that both vibro-tactile and EMS feedbacks offered a somatosensory confirmation to the participants when improper posture was detected, and

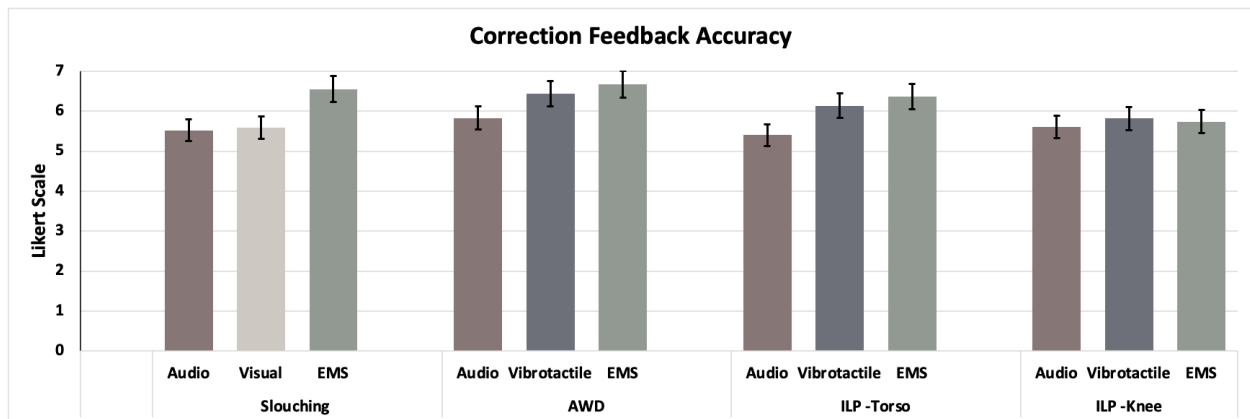


Figure 6.2: User Perception of Correction Feedback Accuracy for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI.

subsequently corrected while the audio and visual feedbacks required more attention, and cognitive processing to understand the feedback information, assess their current posture, self-correct their posture, and receive confirmation feedback that posture had been corrected. It was also interesting to note that user perception of correction feedback accuracy for the audio and visual feedbacks was affected by the level of engagement in the tasks especially in the mobile game tasks in the slouching, and the AWD correction studies due to the presence of in-game sounds. However, the vibro-tactile, and EMS feedback accuracy was relatively unaffected by the task engagement due to their somatosensory confirmations of poor and corrected postures. This illustrates that participants perceived both vibro-tactile and EMS feedback equally accurately due to the distinct and discrete somatosensory experience they offered. This also demonstrated EMS feedbacks' viability as an alternative feedback mechanism with an added advantage of automatic correction in a varied range of tasks with different levels of engagement and posture awareness.

## 6.4 Comfort and Task Disruption

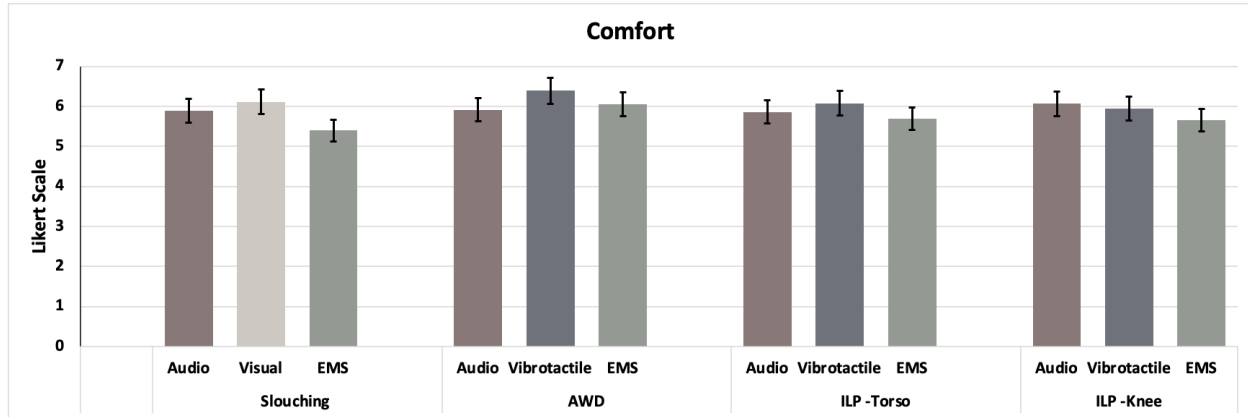


Figure 6.3: User Perception of Comfort for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI

Comfort and task disruption are two important user experience parameters used to determine the usability and feasibility of a technique. From our studies, it was clear that EMS feedback was perceived equally comfortable, and disruptive as the alternative traditional feedback mechanisms. It was interesting to note that the tasks with different levels of engagement and posture awareness had no influence on the perceived level of comfort and disruption of the participants in the EMS feedback. Although a non-invasive feedback mechanism, EMS was known to deliver strong somatosensory experiences to the participants due to its inherent ability to produce muscle contractions involuntarily. However, careful calibration of EMS to an optimal level allows a beneficial trade off between comfort, and desired level of muscular contraction for affecting involuntary posture correction. It was also interesting to note that the level of comfort shared an inverse relationship with task disruption as illustrated from Figures 6.3 and 6.4. Additionally, participants also reported shared responsibilities in helping/aiding the EMS based auto-correction feedback with a mean ranking of 2.29 on a 7-point Likert scale where 1 means not at all and 7 means completely. This indicated the



participants adaptability to new technology, willingness to get involved in the correction process, and also demonstrated the fast learning effects produced by EMS feedback for maintaining, and developing healthy postural habits. EMS being perceived equally comfortable and disruptive as the other alternative feedback mechanisms illustrates the users' adaptability to new technology, and an acceptance of new techniques for maintenance of healthy posture. This shows EMS feedback based posture correction devices' potential to be developed as a commercial product for rehabilitation, preventive health care, and every day use during work and recreational activities.

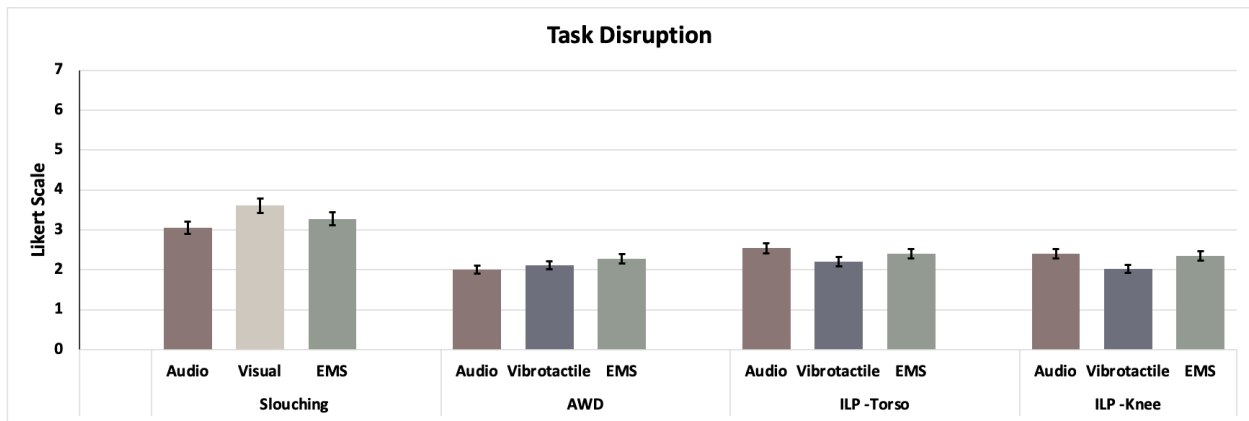


Figure 6.4: User Perception of Task Disruption for correcting Slouching, AWD, ILP Torso Inclination, ILP Knee Bend across different modalities . Error bars: 95% CI

## 6.5 Frequency of Correction

To determine if EMS-based automatic feedback enabled posture awareness and learning effects, we investigated the frequency of corrections delivered to the participants across different modalities in each of the studies. In the slouching study, the average frequency of slouching corrections delivered to the participants across the text entry and the mobile game applications was (7.39, 9.56, 8.56) for the audio, visual, EMS modalities respectively (illustrated in Figure 6.5 (A)). In the AWD study, the average frequency of AWD corrections delivered to the participants across the quiet standing and

the mobile game applications was (12.3, 13.45, 13.3) for the audio, vibro-tactile, EMS modalities respectively (illustrated in Figure 6.5 (B)). In the ILP study, the average frequency of ILP corrections delivered to the participants across both correction strategies was (3.72, 4.52, 3.83) for the audio, vibro-tactile, EMS modalities respectively (illustrated in Figure 6.5 (C)).

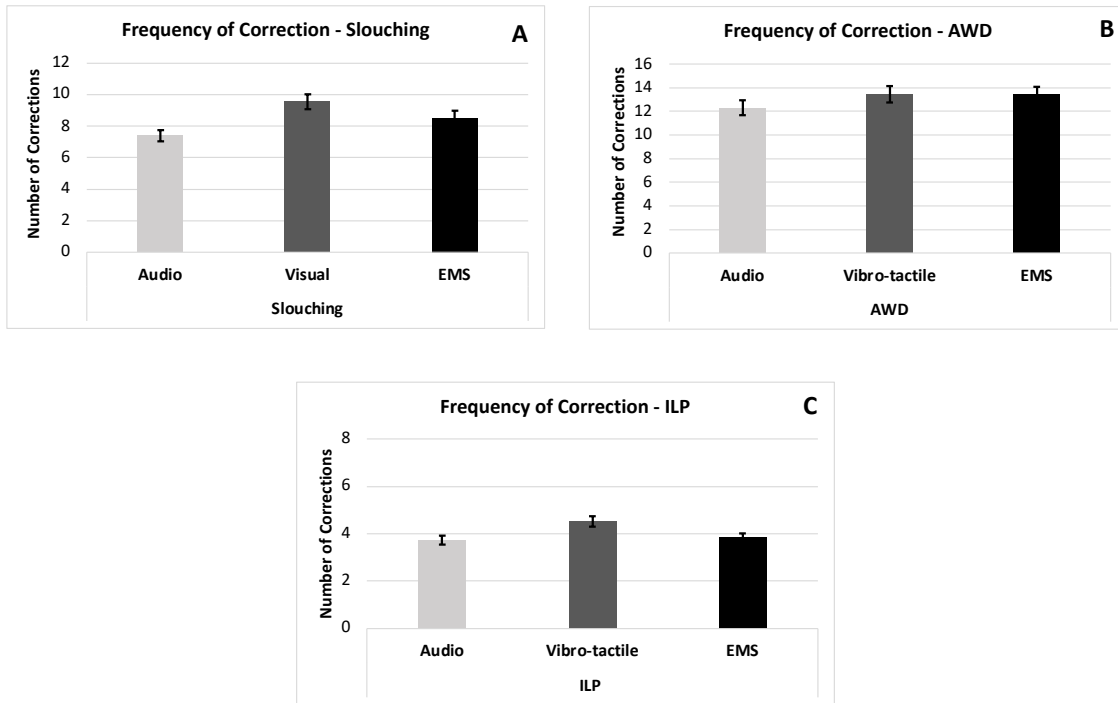


Figure 6.5: Frequency of Corrections: (A) Slouching, (B) AWD, (C) ILP. Error bars: 95% CI.

Further, to investigate the learning effects produced by EMS-based automatic feedback, one-way repeated measures ANOVA were performed on the influence of correction feedback type on the time between the delivered corrections for correcting slouching, AWD, and ILP separately. All effects were statistically significant at the .05 significance level.

In the case of slouching, the main effect for the correction feedback type yielded  $F(2, 70) = 4.133, p < 0.05$ , indicating a significant difference in the time between corrections between the vi-

sual feedback ( $M = 2.16, S.D = 1.03$ ), audio feedback ( $M = 1.93, S.D = 0.82$ ), and EMS feedback ( $M = 2.36, S.D = 0.77$ ) (illustrated in Figure 6.6 (A)). The EMS feedback demonstrated longer times between the corrections in comparison to the audio and visual feedbacks, and hence shows signs of a learning effect towards maintenance of upright posture.

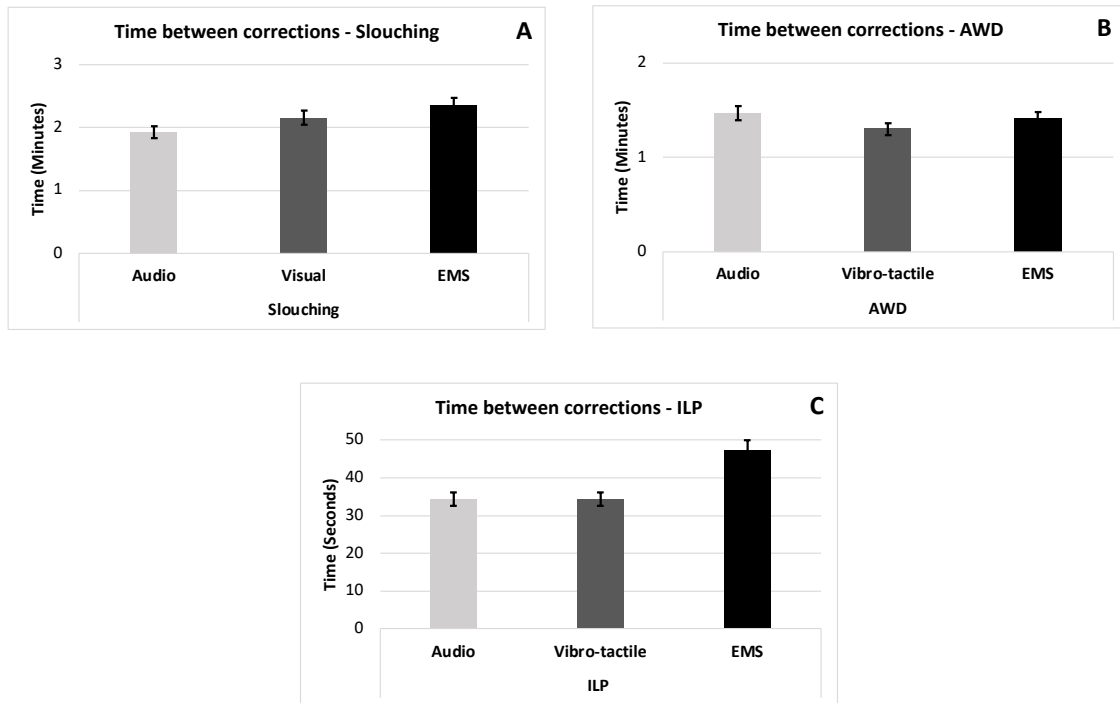


Figure 6.6: Time between Corrections: (A) Slouching, (B) AWD, (C) ILP. Error bars: 95% CI.

In the case of AWD, the main effect for the correction feedback type yielded  $F(2, 70) = 0.686, p > 0.5$ , indicating no significant difference in the time between corrections between the audio feedback ( $M = 1.47, S.D = 0.61$ ), vibro-tactile feedback ( $M = 1.3, S.D = 0.44$ ), and EMS feedback ( $M = 1.41, S.D = 1.13$ ) (illustrated in Figure 6.6 (B)). The EMS feedback demonstrated similar times between corrections as the other two feedback mechanisms.

In the case of ILP, the main effect for the correction feedback type yielded  $F(2, 70) = 3.81, p < 0.05$ ,

indicating a significant difference in the time between corrections between the audio feedback ( $M = 34.36, S.D = 19.68$ ), vibro-tactile feedback ( $M = 34.35, S.D = 19.33$ ), and EMS feedback ( $M = 47.58, S.D = 35.47$ ) (illustrated in Figure 6.6 (C)). The EMS feedback demonstrated approximately 25% longer times between the corrections in comparison to the audio and vibro-tactile feedbacks, and hence shows positive signs of a learning effect towards maintenance of good lifting posture with low torso inclination and high knee bend. Additionally, this learning effect may also be due to the fact that each modality in the ILP Study lasted 5 minutes and participants may have become more aware of their posture and retained information about proper lifting posture after they received the first few ILP corrections.

## 6.6 Feasibility

Due to its relatively compact size, minimal hardware, and compatibility with wireless technology, EMS based feedback can be made portable to allow everyday use in work and home settings. Additionally, EMS demonstrated its ability to perform across posture problems in a range of activity levels ranging from sedentary (Slouching), moderate (AWD), and highly dynamic (ILP) indicating its ability to deliver fast, automatic, and comfortable posture correction under different scenarios such as typing, gaming, standing, and lifting, with different levels of engagement, and posture awareness. Participants ranked very highly for EMS feedback being an interesting approach for automatic posture correction with mean ranking of 6.53 for slouching correction, 6.63 for AWD correction, and 6.69 for ILP correction on 7-point Likert scale where 1 means not at all interesting, and 7 means highly interesting. Additionally, in each of our studies, nearly 55% of our study populations preferred EMS feedback for correcting their poor posture. However, interestingly, approximately 75% of our slouching study population, 80.55% of our AWD study population, and 72% ILP study population were willing to purchase an EMS based wearable automatic slouching,

AWD, and ILP intervention devices respectively, if it were commercially available products. All these factors indicate a strong acceptance and potential for developing EMS feedback as a feasible wearable intervention technology for automatic posture correction.

Finally, our EMS based automatic posture control systems could be particularly beneficial as a wearable intervention device for mitigation RSI, and incidents of work place injury while improving employee health, and safety. Our automatic slouching detection and correction system would be particularly beneficial to students and employees working long hours in sedentary positions, while our automatic AWD detection and correction system would be advantageous for development of rehabilitation protocols for recovery in post-knee/ankle surgery to minimize time duration for return-to-sport in case of athletes or return-to-normal function in case of non-athlete patients. Our automatic ILP correction system would be particularly useful for manual laborers, and construction workers who are involved with lifting and moving loads. Further, our EMS based automatic posture control systems can also be extended to solve posture and gait problems, fall prediction and prevention systems, and interactive applications for delivering kinesthetic experiences in VR, AR and mixed reality applications.

The next chapter discusses the limitations of our work, and proposals for future work.

## CHAPTER 7: LIMITATIONS AND FUTURE WORK

### 7.1 Limitations

The main limitations of our EMS feedback approach include sensor and electrode placement, calibration, muscle fatigue, and mobility. These limitations are discussed below.

#### *7.1.1 Sensor and Electrode Placement*

One prominent limitation was sensor and electrode placement. Identifying sensor placement, and electrode placement locations presented challenges as each participant was different with different physiology, and muscular density. EMS electrode placement locations played an important role in invoking the desired involuntary muscular contraction. For more pronounced and accurate muscular contractions, EMS electrodes were required to be placed on the motor points of the target muscle group to generate a desired physiological response of correcting the poor posture. To resolve this, we plan to integrate the sensors and electrodes into wearable clothing designed to suit a majority of the population.

#### *7.1.2 Calibration*

Another limitation is that calibration of the EMS intensity needs to be done carefully with emphasis on user comfort, and safety while achieving the desired muscle contraction to generate a physiological response necessary for correcting the poor posture. Calibrating each individual for optimal EMS intensity plays a crucial role in ensuring the correct stimulation intensity for invoking muscular contraction, and also deliver a comfortable and smooth experience to the user. For some

participants manual calibration of EMS intensity took longer due to participant unresponsiveness, and also presented the need for constant verbal interaction with the participant to determine the optimal EMS intensity for invoking an involuntary muscular contraction. At each increment of the EMS intensity, participants were required to verbally respond to the researcher's questions on their level of comfort, pain, and how strong the EMS intensity felt at that increment. To address this issue with calibration, an AI based auto-calibration system that can customize to each individual's comfort and responsiveness needs to be developed.

### *7.1.3 Muscle Fatigue*

As this work was primarily focussed on the capabilities of EMS feedback to correct poor posture through involuntary muscular contractions and the effectiveness of our automatic approach, the effects of EMS on muscle fatigue for longer durations and in long term regular usage have not been investigated. A longitudinal study on the benefits of using an automatic EMS feedback based poor posture detection and correction system needs to be conducted to determine if EMS based posture correction was able to prevent poor postural habits and reinforce new good posture habits in the long run. Additionally, longitudinal studies on the effects of EMS based posture correction on productivity, and health and well being also need to be investigated.

### *7.1.4 Mobility*

As our research experiments were constrained to the study area, our systems did not require wireless capabilities. All communication between the user interface application and the EMS module was through wired USB cables. However, this may not be practically viable in a fast paced working environment or at home during every day activities. The addition of a wireless communication protocol to the modules will greatly enhance the mobility and portability of our system and allow

for integration into wearable intervention devices that can be utilized in everyday work or home settings.

#### *7.1.5 Gender Imbalance in the Study Population*

Another limitation of our research was the gender imbalance in our human subject study populations. The male to female ratio in the slouching study was approximately 6:1, while in the AWD study it was approximately 4:1, and in the ILP study 1 it was 2.5:1 and in ILP study 2 it was 1.5:1. A total of 33 females participated in all our studies combined in comparison to 99 male participants. As all our studies were conducted during the COVID-19 pandemic, we saw more male participants who were willing to participate in the studies in comparison to the female participants, in spite of the COVID-19 protocols and safe distancing practices in place. However, the male to female participant ratio gradually improved from 6:1 in the slouching study (July 2020) to 1.5:1 in the ILP study 2 (November 2021) during the later stages of the pandemic. Additionally, the physical nature and long study durations of our studies could have been an influencing factor for less female participation.



## 7.2 Future Work

We have demonstrated the capabilities of EMS based feedback systems in affecting posture correction and this has presented more opportunities for developing exciting and interactive systems in the future. Some of our other future work are described below.

### *7.2.1 Further investigation*

As all our research was conducted with a young adult population in the age group of 18-35 years, further research needs to be conducted on different age group brackets of 35-50 years, and 50-65 years to fully understand the effects of EMS on automatic posture correction. Additionally, our automatic posture correction through EMS feedback needs to be investigated in a comparative study between healthy and poor posture affected populations.

In the case of slouching, our automatic correction approach was evaluated through two different contexts and levels of engagement. Our future work includes evaluating our automatic approach through EMS feedback under different physical contexts such as standing and walking with different loads on their backs, and under different levels of engagement such as being idle, using social media on a smart phone, and low/highly engaging games.

In the case of AWD, our EMS-based automatic correction was evaluated under two different contexts and levels of posture awareness. Our future work includes evaluating our EMS-based automatic approach different physical contexts such as carrying different loads on their backs, and under different levels of engagement such as being idle, having a conversation, social media use, watching a presentation, and low/highly engaging games.

In the case of ILP, we evaluated our ILP automatic correction with four different boxes of different

sizes and loads. Our future work includes investigating EMS-based ILP correction under different types of loads such as boxes, and weighted bags, under different weights ranging from 20-100 lbs, and for different kinds of lifting techniques.

### 7.2.2 Voice activated EMS

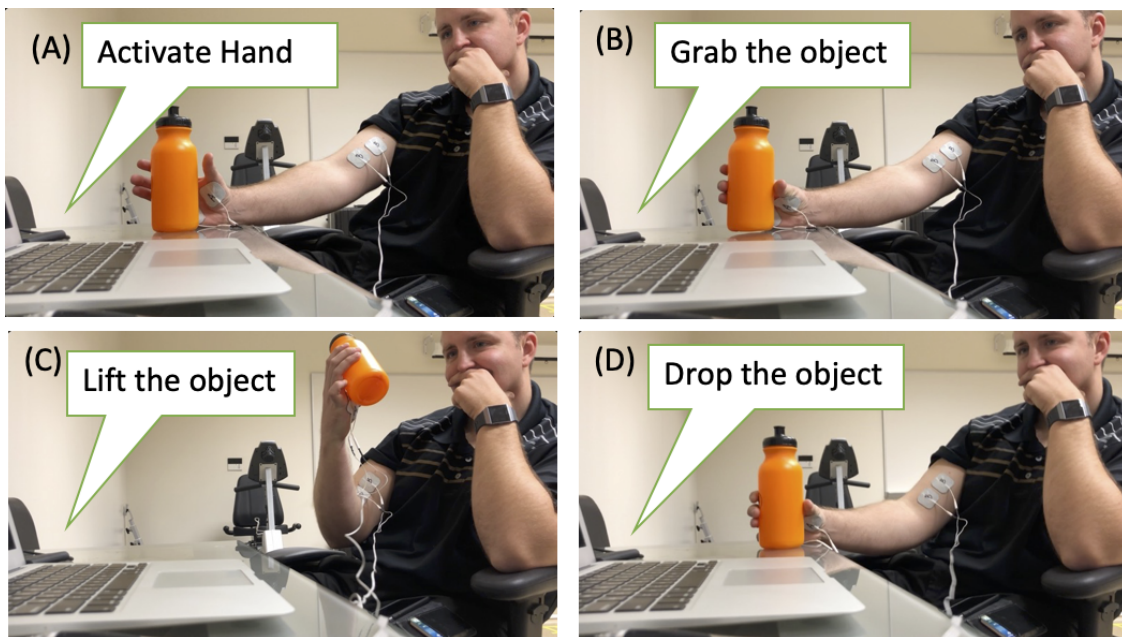


Figure 7.1: Voice activated EMS prototype responding to specific voice commands recognized by the speech recognition engine for (A) Activation of EMS on hand, (B) EMS invoking involuntary contraction of hand muscles for grasping object, (C) EMS invoking involuntary contraction of Bicep muscles for lifting object, (D) Deactivation of EMS on bicep for dropping object.

To extend the capabilities of EMS and its ability to enable motor function in quadriplegic or paralysed patients, we integrated EMS with a speech recognition engine to activate EMS to extend mobility to the hand for performing grasp and lifting functions. Our prototype employed a Microsoft Speech recognition engine to recognize device wake-up words, phrases and sentences. Our speech recognition engine was integrated with a speech library and programmed to recognize specific voice

commands such as “Activate hand”, “Grab the object”, “Lift the object”, “Drop the Object”, and “Deactivate hand”. Our prototype was able to demonstrate activating EMS on the muscles of the hand and arm to perform grasping and lifting actions when the correct commands were delivered as illustrated in Figure 7.2. The integration of speech recognition with EMS presents opportunities for developing rehabilitation protocols for remote physiotherapy and products to extend motor function in paralysed, stroke, and PD patients.

### 7.2.3 Human Tele-Operation

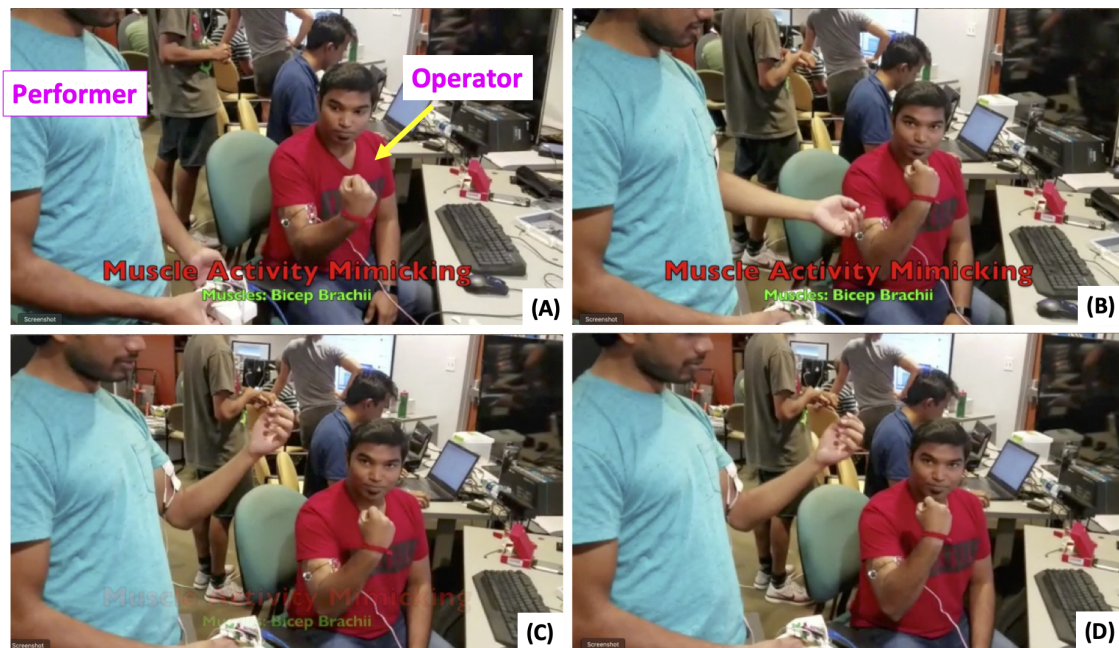


Figure 7.2: Human Tele-operation EMS prototype demonstrating the transfer of muscle activity from Operator to Performer. (A) The operators’ bicep fitted with EMG sensors records muscle activity during a bicep flex action. (B), (C), and (D) The operators’ EMG signal representative of the bicep muscle activation is applied as an electrical stimulus to the bicep muscle performer to generate the same physiological response of the bicep flex action.

We further extended the capabilities of EMS to develop a novel interaction technique for human tele-operation and for dynamic activity training using electromyography (EMG) and electrical muscle stimulation. We explored the transference of muscle activity between people to enable remote tele-operation. This technique presents new possibilities and applications in rehabilitation and dynamic activity training in physical reality and virtual/augmented reality applications.

Our system utilized EMG sensors to record muscle activity on one person (Operator) and reproduced the same muscle activity on another person (Performer) through the application of the EMG signal as an EMS stimulation pattern to the same muscles on the performer. The EMS applied to the same muscle on the performer invokes an involuntary muscular response which mimics the original muscle activity from the operator in real-time. This presents an opportunity to develop sports training protocols for learning new movements and improve muscle memory to enhance performance. Human tele-operation may also allow development of art, dance, martial arts programs to transfer muscle activity from a coach/teacher to an athlete/student to develop fast learning capabilities.

#### *7.2.4 Automatic Detection and Correction of Wrist Extension*

RSI to the wrist represent significant risk factors leading to serious long-term injuries, such as carpal tunnel syndrome, shoulder, and neck pain. Wrist extension is a common posture related issue experienced by many young adults, desk job employees, and programmers who are prone to working for long durations at their computers for work/gaming activities. We developed "Correct-Me", a real-time physiological feedback system that employed bend sensors to actively detect stress on the wrist and dynamically correct improper wrist posture and extension utilizing EMS. We developed a novel flexible 3D printed glove instrumented with embedded bend sensors for detection of wrist positions and integration with EMS (illustrated in Figure 7.3).

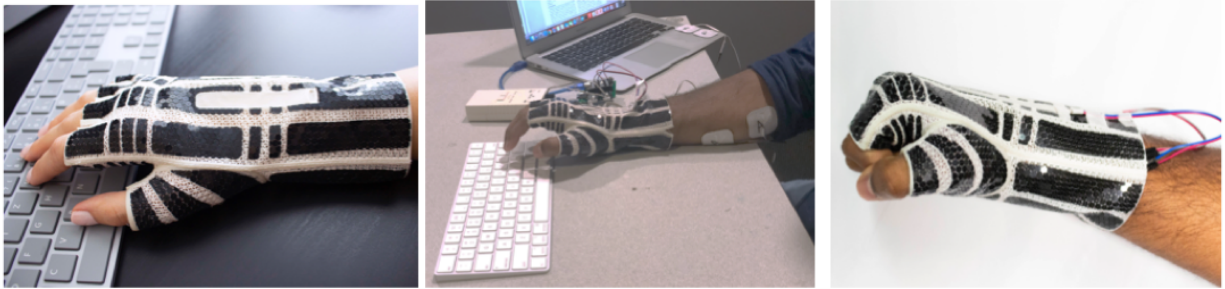


Figure 7.3: Correct-Me: A flexible 3D printed glove with embedded bend sensors to automatically detect and correct wrist extension.



(a) Wrist in extended position.



(b) Wrist extension corrected using EMS

Figure 7.4: Correct-Me: Automatic detection and correction of wrist extension.

Correct-Me continuously monitors the wrist for extension which is obtained from bend sensors placed strategically in the glove on the back of the hand at the wrist joint. When wrist extension is detected (illustrated in Figure 7.4a), EMS was automatically applied to the forearm to invoke an involuntary muscular contraction which generates a physiological response of restoring the wrist back to neutral position and thereby correcting wrist extension (illustrated in Figure 7.4b). Future work includes conducting a human subject study to determine the effectiveness of our automatic approach against traditional audio, visual, vibrotactile feedback systems in an ecologically valid setting such as typing, drawing, and gaming.

### 7.2.5 *Automatic Detection and Correction of Poor Neck Posture*

RSI to the neck present risk factors that lead to strain, soreness, intense pain in the neck muscles. We further extended our Correct-Me system to detect and correct neck cradling, and forward neck. Poor neck posture is a common posture related issue experienced by people who are prone to long durations at their computers/smartphones for work, gaming, and social media activities. We developed a real-time physiological feedback system that employed bend sensors to actively detect stress on the neck and dynamically correct improper neck posture and utilizing EMS. An array of bend sensors placed around the neck detected neck cradling or forward neck by the stress placed on them. When poor neck posture was detected, EMS was automatically applied to the trapezius muscles to invoke an involuntary muscular contraction that generates a physiological response of straightening the neck. Future work includes conducting a human subject study to determine the effectiveness of our automatic approach against traditional audio, visual, vibrotactile feedback systems in an ecologically valid setting such as gaming or typing.

Our other future work includes:

- Design, development, and evaluation of a fall prediction and prevention system utilizing EMS.
- Design, development, and evaluation of a system to automatically protect the head in case of slips or falls.
- Design, development, and evaluation of gait irregularities correction systems.
- Design, development, and evaluation of a multi-array EMS system to simultaneously support more muscles of the hand, torso, legs to increase mobility and functional capabilities.
- Design, development, and evaluation of a mobile application to allow participants to customize

their preferences of sensor thresholds, and EMS intensity to their sensitivity and comfort.

- Design, development, and evaluation of an interactive virtual assistant to recognize a series of commands, and develop AI capabilities for multi-array muscle stimulation to accomplish more complex tasks and even multi-tasking.

## CHAPTER 8: CONCLUSION

We have demonstrated the integration of sensor based poor posture detection with automatic EMS feedback based correction, and the design and development of a physiological feedback loop based on automatic poor posture detection and correction systems for slouching, AWD, and ILP. Our automatic EMS based correction systems delivered approximately 30% to 45% faster corrections in comparison to the alternative traditional feedback systems. Our automatic EMS feedback approach was also perceived to be highly accurate, equally comfortable and disruptive, and was highly effective across a range of applications with varying levels of engagement and posture awareness.

For automatic slouching detection and correction, our auto-correction system utilizing EMS feedback demonstrated faster posture correction response times compared to the self-correction in the visual and audio feedback. Our approach also showed that users perceived EMS feedback to be more accurate, just as comfortable and produced no more disruption than the alternative techniques it was tested against in both the text entry and the mobile game applications. Approximately 75% of the study population was willing to purchase an automatic EMS based wearable intervention for correcting slouching. Therefore, automatic slouching detection and correction utilizing EMS shows promising results and can be developed as an alternative method for posture correction. Our approach could prove useful in preventive healthcare to avoid workplace related RSI and be particularly beneficial to people involved in highly engaging tasks such as gaming, diagnostic monitoring, and defense control tasks.

For automatic AWD detection and correction, our auto-correction system utilizing EMS feedback delivered significantly faster corrections compared to the self-correction in the audio and vibrotactile feedback. Our approach also showed that participants perceived EMS feedback to be highly accurate, equally comfortable, and produced no more disruption than the alternative techniques



it was tested against in both the quiet standing and the mobile game applications even though the posture awareness across the application types were significantly different. Approximately 82% of the study population was willing to purchase an automatic EMS based wearable intervention device for correcting AWD. Therefore, automatic AWD detection and correction utilizing EMS shows promising results and can be developed as an alternative method for AWD correction especially in preventive health care, for the development of rehabilitation protocols for recovery post-knee/ankle surgery, and everyday use especially by younger adults engaging in the use of mobile devices for gaming, social media activities while standing, and older adults engaging in work related activities in industrial, manufacturing or customer service sectors that require long standing hours.

For automatic ILP detection and correction, we have demonstrated that our physiological feedback loop based on automatic ILP detection and correction with EMS feedback is a viable approach to supporting ILP correction while stabilizing torso and knee bending towards ideal lifting angles to prevent risk of injury. Our auto-correction system utilizing EMS feedback demonstrated significantly faster ILP correction response times compared to the self-correction in the audio and vibro-tactile feedback. Our approach also showed that participants perceived EMS feedback to be highly accurate, equally comfortable, and produced no more disruption than the alternative techniques it was tested against in both the torso inclination and knee bend correction strategies. Approximately 72% of the study population was willing to purchase an automatic EMS based wearable intervention device for correcting ILP. Therefore, our autonomous ILP detection and correction system utilizing EMS shows promising results and could be a useful alternative or inclusion to the existing environment, health, and safety (EHS) guidelines for mitigating risk of workplace injury, improving employee health, and preventive health care.

In conclusion, we have demonstrated that our physiological feedback loop based on automatic poor posture detection and correction with EMS is a viable approach to supporting posture correction and shows promising potential for the development of embedded sensor based wearables intervention

technology for detecting and correcting poor postures.

**APPENDIX A: HUMAN SUBJECT STUDY**  
**QUESTIONNAIRES-SLOUCHING**

## Pre-Questionnaire

**Study: Slouching Detection and Correction**

Participant No.

### Pre-Questionnaire

This questionnaire asks you to answer questions about your prior experience and knowledge of the field. You will also be asked to answer some questions regarding concepts related to poor posture and feedback mechanisms.

1. How frequently do you use a computer [1= not frequently, 7=very frequently]

1    2    3    4    5    6    7

2. How frequently do you experience posture problems at workplace [1= Never, 7=very frequently]

1    2    3    4    5    6    7

3. Please rate your if you have ever experienced slouching while at work [1=Never, 7=Frequently].

1    2    3    4    5    6    7

4. Do you use any health improving devices? (if so, please name them)

No

If Yes, names:

|

5. Please rate your current experience and knowledge of Posture alert / correction devices [1=very little experience/knowledge, 7=very experienced and knowledgeable]

1    2    3    4    5    6    7

6. Please rate your current experience and knowledge of Electrical Muscle Stimulation (EMS). [1=very little experience/knowledge, 7=very experienced and knowledgeable about EMS].

1    2    3    4    5    6    7

7. Which of the following posture problems are you aware of (circle all that apply):

a. Wrist Extension

c. Neck cradling

b. Slouching

d. Uneven weight distribution (Legs)

e. Any others (please specify)

## Post-Questionnaire Audio Modality

**Study: Slouching Detection and Correction (A)**

Participant No.

Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your slouched posture [1= not accurate, 7= very accurate]

1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your slouched posture [1= not accurate, 7= very accurate]

1    2    3    4    5    6    7

4. Did the system help with correcting your slouched posture [1=Strongly Disagree, 7=Strongly Agree]

1    2    3    4    5    6    7

5. How comfortable were you in the Audio modality ? [1=Completely uncomfortable, 7=Completely Comfortable]

1    2    3    4    5    6    7

6. How engaged were you during the task [1= not at all, 7= completely]

1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

1    2    3    4    5    6    7

8. Would you use the audio feedback if it became a commercial product?

Yes    No

## Post-Questionnaire Visual Modality

**Study: Slouching Detection and Correction (v)**

Participant No.

Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the visual alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1      2      3      4      5      6      7

2. How accurately do you think the system detected your slouched posture [1= not accurate, 7= very accurate]

1      2      3      4      5      6      7

3. How accurately do you think the system presented correction feedback for your slouched posture [1= not accurate, 7= very accurate]

1      2      3      4      5      6      7

4. Did the system help with correcting your slouched posture [1=Strongly Disagree, 7=Strongly Agree]

1      2      3      4      5      6      7

5. How comfortable were you in the visual modality ? [1=Completely uncomfortable, 7=Completely Comfortable]

1      2      3      4      5      6      7

6. How engaged were you during the task [1= not at all, 7= completely]

1      2      3      4      5      6      7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

1      2      3      4      5      6      7

8. Would you use the visual feedback if it became a commercial product?

Yes    No

## Post-Questionnaire EMS Modality

**Study: Slouching Detection and Correction (E)**

Participant No.

Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the EMS alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1      2      3      4      5      6      7

2. How accurately do you think the system detected your slouched posture [1= not accurate, 7= very accurate]

1      2      3      4      5      6      7

3. How accurately do you think the system presented correction feedback for your slouched posture [1 not accurate, 7= very accurate]

1      2      3      4      5      6      7

4. Did the system help with correcting your slouched posture [1=Strongly Disagree, 7=Strongly Agree]

1      2      3      4      5      6      7

5. How comfortable were you in the EMS modality ? [1=Completely uncomfortable, 7=Completely Comfortable]

1      2      3      4      5      6      7

6. How engaged were you during the task [1= not at all, 7= completely]

1      2      3      4      5      6      7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

1      2      3      4      5      6      7

8. Would you use the EMS feedback if it became a commercial product?

Yes      No

## Post-Questionnaire Comparative

**Study: Slouching Detection and Correction**

Participant No. \_\_\_\_\_

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1a. Please rate your overall experience with the visual alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1      2      3      4      5      6      7

1b. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1      2      3      4      5      6      7

1c. Please rate your overall experience with the EMS modality and auto correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1      2      3      4      5      6      7

2. Which of the 3 feedback modalities did you like most/least?

- a. Visual Alert Modality and Self correction
- b. Audio Alert Modality and Self correction
- c. EMS Modality and Automatic correction

Why? \_\_\_\_\_

3. Please describe what you liked / disliked about each modality

- a. Visual Alert Modality and Self correction
  
- b. Audio Alert Modality and Self correction
  
- c. EMS Modality and Automatic correction

4. How accurately do you think the system detected your slouched posture [1= not accurate, 7= very accurate]

1      2      3      4      5      6      7



5. How accurately do you think the system presented correction feedback for your slouched posture [1= not accurate, 7= very accurate]

1      2      3      4      5      6      7

6. Did the system help with correcting your slouched posture [1=Strongly Disagree, 7=Strongly Agree]

a. Visual Modality:      1      2      3      4      5      6      7

b. Audio Modality:      1      2      3      4      5      6      7

c. EMS Modality:      1      2      3      4      5      6      7

7. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

a. Visual Modality:      1      2      3      4      5      6      7

b. Audio Modality:      1      2      3      4      5      6      7

c. EMS Modality:      1      2      3      4      5      6      7

8. How engaged were you during the task [1= not at all, 7= completely]

a. Visual Modality:      1      2      3      4      5      6      7

b. Audio Modality:      1      2      3      4      5      6      7

c. EMS Modality:      1      2      3      4      5      6      7

9. Did the correction disrupt you from your task [1= not at all, 7= completely]

a. Visual Modality:      1      2      3      4      5      6      7

b. Audio Modality:      1      2      3      4      5      6      7

c. EMS Modality:      1      2      3      4      5      6      7

10. In the EMS Modality, did you help/aid the auto correction? [1= not at all, 7= completely]

1      2      3      4      5      6      7

11. How do you perceive the use of EMS and auto correction?

12. The EMS concept was interesting to use. [1=Strongly Disagree, 7=Strongly Agree]

1      2      3      4      5      6      7

13a. Would you use the visual feedback if it became a commercial product?

Yes      No

13b. Would you use the audio feedback if it became a commercial product?

---

Yes No

13c. Would you use the EMS feedback if it became a commercial product?

Yes No

14. What other applications do you think this system could be used for?

15. How much has this experiment increased your awareness of the posture issues? [1=Not at all, 7=Very much]

1 2 3 4 5 6 7

16. Do you have any other comments about your experience?

## **APPENDIX B: HUMAN SUBJECT STUDY QUESTIONNAIRES-AWD**

# Pre-Questionnaire

Q  
M

**Study: AWD**

Participant No.  
Order:

## Pre-Questionnaire

This questionnaire asks you to answer questions about your prior experience and knowledge of the field. You will also be asked to answer some questions regarding concepts related to poor posture and feedback mechanisms.

1. How frequently do you work / play mobile games while standing [1= not frequently, 7=very frequently]  
1    2    3    4    5    6    7
2. On average, how many hours/ minutes in a day do you do standing activities. [1= 1 Hr, 7= 7Hrs]  
1    2    3    4    5    6    7
3. How frequently do you experience posture problems due to prolonged standing at workplace [1= Never, 7=very frequently]  
1    2    3    4    5    6    7
4. Please rate your if you have ever experienced asymmetric weight distribution (leaning on either leg or shifting weight to one leg) [1=Never, 7=Frequently].  
1    2    3    4    5    6    7
5. Do you use any health improving devices? (If so, please name them) |  
No                      If Yes, names:
6. Please rate your current experience and knowledge of balance alert / correction devices [1=very little experience/knowledge, 7=very experienced and knowledgeable]  
1    2    3    4    5    6    7
7. Please rate your current experience and knowledge of Electrical Muscle Stimulation (EMS). [1=very little experience/knowledge, 7=very experienced and knowledgeable about EMS].  
1    2    3    4    5    6    7
8. Which of the following posture problems are you aware of (circle all that apply):
  - a. Wrist Extension
  - b. Slouching
  - c. Neck cradling
  - d. Asymmetric weight distribution (Legs)
  - e. Any others (please specify)

## Post-Questionnaire Audio Modality

Q  
M

Study: AWD(Audio)

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your AWD [1= not accurate, 7= very accurate]

a. Audio Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your AWD [1= not accurate, 7= very accurate]

a. Audio Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your AWD [1=Strongly Disagree, 7=Strongly Agree]

a. Audio Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

a. Audio Modality:    1    2    3    4    5    6    7

6. How engaged were you during the task [1= not at all, 7= completely]

a. Audio Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

a. Audio Modality:    1    2    3    4    5    6    7

8. Would you use the audio feedback if it became a commercial product?

Yes    No

## Post-Questionnaire Vibro-tactile Modality

Q  
M

**Study: AWD(Vibration)**

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the vibration alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your AWD [1= not accurate, 7= very accurate]

b. Haptic Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your AWD [1= not accurate, 7= very accurate]

b. Haptic Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your AWD [1=Strongly Disagree, 7=Strongly Agree]

b. Haptic Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

b. Haptic Modality:    1    2    3    4    5    6    7

6. How engaged were you during the task [1= not at all, 7= completely]

b. Haptic Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

b. Haptic Modality:    1    2    3    4    5    6    7

8. Would you use the haptic feedback if it became a commercial product?

Yes    No

## Post-Questionnaire EMS Modality

Q  
M

Study: AWD(EMS)

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the EMS alert modality and auto correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your AWD [1= not accurate, 7= very accurate]

c. EMS Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your AWD [1= not accurate, 7= very accurate]

c. EMS Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your AWD [1=Strongly Disagree, 7=Strongly Agree]

c. EMS Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

c. EMS Modality:    1    2    3    4    5    6    7

6. How engaged were you during the task [1= not at all, 7= completely]

c. EMS Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

c. EMS Modality:    1    2    3    4    5    6    7

8. Would you use the EMS feedback if it became a commercial product?

Yes    No

## Post-Questionnaire Comparative

Q  
M

**Study: AWD (Overall)**

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1a. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

1b. Please rate your overall experience with the vibration alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

1c. Please rate your overall experience with the EMS alert modality and auto correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. Which of the 3 feedback modalities did you like most/least?

- a. Audio Alert Modality and Self correction
- b. Haptic Alert Modality and Self correction
- c. EMS Modality and Automatic correction

Why? \_\_\_\_\_

3. Rank the 3 Feedback modalities on the overall experience: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_

Haptic Alert Modality and Self correction \_\_\_\_\_

EMS Modality and Automatic correction \_\_\_\_\_

4. Please describe what you liked / disliked about each modality

- a. Audio Alert Modality and Self correction
  
  
- b. Haptic Alert Modality and Self correction
  
  
- c. EMS Modality and Automatic correction



Q  
M

5. How accurately do you think the system detected your AWD [1= not accurate, 7= very accurate]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

5.a Rank the 3 Feedback modalities on the Accuracy of detection of AWD: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_

Haptic Alert Modality and Self correction \_\_\_\_\_

EMS Modality and Automatic correction \_\_\_\_\_

6. How accurately do you think the system presented correction feedback for your AWD [1= not accurate, 7= very accurate]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

6.a Rank the 3 Feedback modalities on the Accuracy of Feedback to AWD: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_

Haptic Alert Modality and Self correction \_\_\_\_\_

EMS Modality and Automatic correction \_\_\_\_\_

7. Did the system help with correcting your AWD [1=Strongly Disagree, 7=Strongly Agree]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

7.a Rank the 3 Feedback modalities on correcting your AWD: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_

Haptic Alert Modality and Self correction \_\_\_\_\_

EMS Modality and Automatic correction \_\_\_\_\_

8. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

Q  
M

8.a Rank the 3 Feedback modalities on Comfort: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_  
Haptic Alert Modality and Self correction \_\_\_\_\_  
EMS Modality and Automatic correction \_\_\_\_\_

9. How engaged were you during the task [1= not at all, 7= completely]

a. Audio Modality: 1 2 3 4 5 6 7  
b. Haptic Modality: 1 2 3 4 5 6 7  
c. EMS Modality: 1 2 3 4 5 6 7

9.a Rank the 3 Feedback modalities on your engagement during the task: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_  
Haptic Alert Modality and Self correction \_\_\_\_\_  
EMS Modality and Automatic correction \_\_\_\_\_

10. Did the correction disrupt you from your task [1= not at all, 7= completely]

a. Audio Modality: 1 2 3 4 5 6 7  
b. Haptic Modality: 1 2 3 4 5 6 7  
c. EMS Modality: 1 2 3 4 5 6 7

10.a Rank the 3 Feedback modalities on Task Disruption: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_  
Haptic Alert Modality and Self correction \_\_\_\_\_  
EMS Modality and Automatic correction \_\_\_\_\_

11. How aware of your posture and balance were you during the task [1= not at all, 7= completely]

a. Audio Modality: 1 2 3 4 5 6 7  
b. Haptic Modality: 1 2 3 4 5 6 7  
c. EMS Modality: 1 2 3 4 5 6 7

11.a Rank the 3 Feedback modalities on Posture awareness: [1=Best, 2= Good, 3=Ok]

Audio Alert Modality and Self correction \_\_\_\_\_  
Haptic Alert Modality and Self correction \_\_\_\_\_  
EMS Modality and Automatic correction \_\_\_\_\_

12. The EMS concept was interesting to use. [1=Strongly Disagree, 7=Strongly Agree]

1 2 3 4 5 6 7

13a. Would you use the audio feedback if it became a commercial product?

Yes No

Q  
M

13b. Would you use the haptic feedback if it became a commercial product?

Yes No

13c. Would you use the EMS feedback if it became a commercial product?

Yes No

14. What other applications do you think this system could be used for?

15. How much has this experiment increased your awareness of the posture issues? [1=Not at all, 7=Very much]

1 2 3 4 5 6 7

16. Do you have any other comments about your experience?

## **APPENDIX C: HUMAN SUBJECT STUDY QUESTIONNAIRES-ILP**

# Pre-Questionnaire

T  
K

Age:            Gender:  
Height:        Weight:

**Study: Improper Loading Posture**

Participant No:

## Pre-Questionnaire

This questionnaire asks you to answer questions about your prior experience and knowledge of the field. You will also be asked to answer some questions regarding concepts related to poor posture and feedback mechanisms.

1. How frequently do you do workout [1= not frequently, 7=very frequently]  
1    2    3    4    5    6    7
2. How frequently do you do deadlifts/ squats [1= not frequently, 7=very frequently]  
1    2    3    4    5    6    7
2. How frequently do you experience posture problems [1= Never, 7=very frequently]  
1    2    3    4    5    6    7
3. Please rate your if you have ever experienced bad loading/ back issues [1=Never, 7=Frequently].  
1    2    3    4    5    6    7
4. Do you use any health improving devices? (if so, please name them)  
No            If Yes, names:
5. Please rate your current experience and knowledge of posture alert / correction devices [1=very little experience/knowledge, 7=very experienced and knowledgeable]  
1    2    3    4    5    6    7
6. Please rate your current experience and knowledge of Electrical muscle stimulation [1=very little experience/knowledge, 7=very experienced and knowledgeable]  
1    2    3    4    5    6    7
7. Which of the following posture problems are you aware of (circle all that apply):
  - a. Wrist Extension
  - b. Slouching
  - c. Neck cradling
  - d. Asymmetric weight distribution (Legs)
  - e. Improper Loading posture

## Post-Questionnaire Audio Modality

Study: ILP(Audio)

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your ILP [1= not accurate, 7= very accurate]

a. Audio Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your ILP [1= not accurate, 7= very accurate]

a. Audio Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your ILP [1=Strongly Disagree, 7=Strongly Agree]

a. Audio Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

a. Audio Modality:    1    2    3    4    5    6    7

6. How aware of your posture were you during the lifting process [1=Completely unaware, 7=Completely aware]

a. Audio Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

a. Audio Modality:    1    2    3    4    5    6    7

8. Would you use the audio feedback if it became a commercial product?

Yes    No

## Post-Questionnaire Vibro-tactile Modality

Study: ILP(Vibration)

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the vibration alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your ILP [1= not accurate, 7= very accurate]

b. Haptic Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your ILP [1= not accurate, 7= very accurate]

b. Haptic Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your ILP [1=Strongly Disagree, 7=Strongly Agree]

b. Haptic Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

b. Haptic Modality:    1    2    3    4    5    6    7

6. How aware of your posture were you during the lifting process [1=Completely unaware, 7=Completely aware]

a. Haptic Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

b. Haptic Modality:    1    2    3    4    5    6    7

8. Would you use the haptic feedback if it became a commercial product?

Yes    No

## Post-Questionnaire EMS Modality

Study: ILP(EMS)

Participant No.

Order:

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1. Please rate your overall experience with the EMS alert modality and auto correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. How accurately do you think the system detected your ILP [1= not accurate, 7= very accurate]

c. EMS Modality:    1    2    3    4    5    6    7

3. How accurately do you think the system presented correction feedback for your ILP [1= not accurate, 7= very accurate]

c. EMS Modality:    1    2    3    4    5    6    7

4. Did the system help with correcting your ILP [1=Strongly Disagree, 7=Strongly Agree]

c. EMS Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

c. EMS Modality:    1    2    3    4    5    6    7

6. How aware of your posture were you during the lifting process [1=Completely unaware, 7=Completely aware]

a. EMS Modality:    1    2    3    4    5    6    7

7. Did the correction disrupt you from your task [1= not at all, 7= completely]

c. EMS Modality:    1    2    3    4    5    6    7

8. Shared Responsibility: How much did you help/ aid the EMS based automatic correction feedback [1= not at all, 7= completely]

1    2    3    4    5    6    7

9. Would you use the EMS feedback if it became a commercial product?

Yes    No



## Post-Questionnaire Comparative

**Study: Improper Loading posture**

Participant No.

### Post-Questionnaire

This questionnaire asks you to answer questions about your experience and some questions regarding the experiment you just participated in.

1b. Please rate your overall experience with the audio alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

1c. Please rate your overall experience with the haptic alert modality and self-correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

1d. Please rate your overall experience with the EMS alert modality and auto correction during this experiment: [1=Strongly disliked it, 7=Strongly liked it]

1    2    3    4    5    6    7

2. Which of the 3 feedback modalities did you like most/least?

- a. Audio Alert Modality and Self correction
- b. Haptic Alert Modality and Self correction
- c. EMS Modality and Automatic correction

Why? \_\_\_\_\_

3. Please describe what you liked / disliked about each modality

- a. Audio Alert Modality and Self correction
  
- b. Haptic Alert Modality and Self correction
  
- c. EMS Modality and Automatic correction

4. Did the system help with correcting your ILP to get into a better lifting/placing posture to lift / place the boxes [1=Strongly Disagree, 7=Strongly Agree]

a. Audio Modality:    1    2    3    4    5    6    7

b. Haptic Modality:    1    2    3    4    5    6    7

c. EMS Modality:    1    2    3    4    5    6    7

5. How comfortable were each of the modalities for you? [1=Completely uncomfortable, 7=Completely Comfortable]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

6. Did the correction disrupt you from your task [1= not at all, 7= completely]

a. Audio Modality: 1 2 3 4 5 6 7

b. Haptic Modality: 1 2 3 4 5 6 7

c. EMS Modality: 1 2 3 4 5 6 7

7. The EMS concept was interesting to use. [1=Strongly Disagree, 7=Strongly Agree]

1 2 3 4 5 6 7

8. Shared Responsibility: How much did you help/ aid the EMS based automatic correction feedback [1= not at all, 7= completely]

1 2 3 4 5 6 7

9. What other applications do you think this system could be used for?

10. How much has this experiment increased your awareness of the posture issues? [1=Not at all, 7=Very much]

1 2 3 4 5 6 7

11. Do you have any other comments about your experience?

## **APPENDIX D: IRB APPROVAL LETTERS**

## IRB APPROVAL LETTER-SLOUCHING



UNIVERSITY OF CENTRAL FLORIDA

**Institutional Review Board**  
FWA0000351  
IRB00001138Office of Research  
12201 Research Parkway  
Orlando, FL 32826-3246

### APPROVAL

January 24, 2020

Dear Ravi Kiran Kattoju:

On 1/24/2020, the IRB reviewed the following submission:

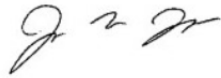
Type of Review:	Initial Study
Title:	Dynamic Activity Training and Posture Correction Using Electrical Muscle stimulation.
Investigator:	Ravi Kiran Kattoju
IRB ID:	STUDY00001033
Funding:	Name: Univ of Central FL
Grant ID:	
IND, IDE, or HDE:	None
Documents Reviewed:	<ul style="list-style-type: none"><li>• FacultyAdvisorReview1_1.pdf, Category: Faculty Research Approval;</li><li>• Flyer.docx, Category: Recruitment Materials;</li><li>• HRP 502_IRB_Edits_Revised, Category: Consent Form;</li><li>• HRP 503_IRB_Edits_Revised, Category: IRB Protocol;</li><li>• postquestionnaire, Category: Survey / Questionnaire;</li><li>• pre questionnaire, Category: Survey / Questionnaire;</li></ul>

The IRB approved the protocol on 1/24/2020.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system.

If you have any questions, please contact the UCF IRB at 407-823-2901 or [irb@ucf.edu](mailto:irb@ucf.edu). Please include your project title and IRB number in all correspondence with this office.

Sincerely,

A handwritten signature in black ink, appearing to read 'Racine Jacques'.

Racine Jacques, Ph.D.  
Designated Reviewer

## IRB APPROVAL LETTER-AWD



UNIVERSITY OF CENTRAL FLORIDA

### Institutional Review Board

FWA00000351  
IRB00001138, IRB00012110  
Office of Research  
12201 Research Parkway  
Orlando, FL 32826-3246

### APPROVAL

July 6, 2021

Dear Ravi Kiran Kattoju:

On 7/6/2021, the IRB reviewed the following submission:

Type of Review:	Initial Study, Category 4
Title:	Asymmetric Weight Distribution Detection and Correction
Investigator:	Ravi Kiran Kattoju
IRB ID:	STUDY00003014
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	<ul style="list-style-type: none"><li>• Faculty Advisor Review, Category: Faculty Research Approval;</li><li>• Audio feedback notification for leaning left, Category: Test Instruments;</li><li>• Audio feedback notification for leaning right , Category: Test Instruments;</li><li>• HRP 503 Protocol, Category: IRB Protocol;</li><li>• HRP-502 Consent , Category: Consent Form;</li><li>• PostQuestionnaire, Category: Survey / Questionnaire;</li><li>• PreQuestionnaire, Category: Survey / Questionnaire;</li><li>• Recruitment Flyer, Category: Recruitment Materials</li></ul>

The IRB approved the protocol from 7/6/2021.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or [irb@ucf.edu](mailto:irb@ucf.edu). Please include your project title and IRB number in all correspondence with this office.

Sincerely,

A handwritten signature in purple ink that reads "Katie Kilgore".

Katie Kilgore  
Designated Reviewer

## IRB APPROVAL LETTER-ILP



UNIVERSITY OF CENTRAL FLORIDA

### Institutional Review Board

FWA00000351  
IRB00001138, IRB00012110  
Office of Research  
12201 Research Parkway  
Orlando, FL 32826-3246

### APPROVAL

July 7, 2021

Dear Ravi Kiran Kattoju:

On 7/7/2021, the IRB reviewed the following submission:

Type of Review:	Initial Study, Category 4
Title:	Improper Loading Posture Detection and Correction
Investigator:	Ravi Kiran Kattoju
IRB ID:	STUDY00003017
Funding:	None
Grant ID:	None
IND, IDE, or HDE:	None
Documents Reviewed:	<ul style="list-style-type: none"><li>• Faculty Advisor Review, Category: Faculty Research Approval;</li><li>• Audio Feedback Notification , Category: Test Instruments;</li><li>• HRP502-Consent, Category: Consent Form;</li><li>• HRP-503-Protocol, Category: IRB Protocol;</li><li>• Post Questionnaire, Category: Survey / Questionnaire;</li><li>• Pre Questionnaire, Category: Survey / Questionnaire;</li><li>• Recruitment Flyer/Email, Category: Recruitment Materials</li></ul>

The IRB approved the protocol from 7/7/2021.

In conducting this protocol, you are required to follow the requirements listed in the Investigator Manual (HRP-103), which can be found by navigating to the IRB Library within the IRB system. Guidance on submitting Modifications and a Continuing Review or Administrative Check-in are detailed in the manual. When you have completed your research, please submit a Study Closure request so that IRB records will be accurate.

If you have any questions, please contact the UCF IRB at 407-823-2901 or [irb@ucf.edu](mailto:irb@ucf.edu). Please include your project title and IRB number in all correspondence with this office.

Sincerely,

A handwritten signature in purple ink that reads "Katie Kilgore".

Katie Kilgore  
Designated Reviewer

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