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LONG-TERM MONITORING OF PERSONS WITH SPINAL CORD INJURY (SCI): IMPLICATION FOR PRESSURE ULCER DEVELOPMENT

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ABSTRACT

FACULTY OF ENVIRONMENTAL AND LIFE SCIENCES

Doctor of Philosophy

LONG-TERM MONITORING OF PERSONS WITH SPINAL CORD INJURY (SCI): IMPLICATION FOR PRESSURE ULCER DEVELOPMENT

By Sarah Fryer

It is well established that persons with Spinal Cord Injury (SCI) are at considerable risk of developing a Pressure ulcer (PU) at all times in their life following injury. This risk is associated with limited mobility coupled with impaired sensation leading to prolonged periods of support in bed or in a wheelchair. Monitoring has traditionally involved short term mapping of pressures on different support surfaces. More recently, pressure mapping systems have been adapted to acquire data over prolonged periods in lying and sitting postures. By identifying sharp transitions in the temporal profiles of selected pressure-related parameters and verifying these with customised software, a comprehensive analysis of posture and mobility can be achieved during each monitoring period. This approach was adopted with a heterogeneous cohort of SCI persons (n=12), who were in-patients at the Duke of Cornwall Spinal Centre and had been judged to be capable of “sitting out” in their wheelchair for at least four hours per day. This represented phase 3 of their rehabilitation, which had been identified in a retrospective analysis to represent a period in which individuals were particularly vulnerable of developing a pressure ulcer.

The first in-patient analysis revealed considerable variation in movement behaviour in both bed and sitting across the cohort. Movements to offload vulnerable areas (MOVA) were explored. Closer examination revealed that two parameters, namely, average number of MOVAs per hour and maximum time between MOVAs. Notable trends were discovered when analysing the aforementioned parameters against the individual SCI level and ASIA score. There were, however, a few outliers to these general trends, which could be associated with specific co-morbidities.

The initial analysis motivated an Individualized Pressure Ulcer Prevention Plan (IPUPP) which was examined with a small proportion (33%) of the cohort who remained as in-patients. This revealed considerable diversity in the second analysis of movement behaviour. In particular, a general improvement was only evident with those individuals who had experienced a previous history of bed rest of skin damage, as confirmed in their associated interviews.

The analysis following discharge to the community, revealed some marked changes to the individual movement behaviour, which could be attributed to a number of factors, including differences in support surfaces to match community settings, carer capacities and individual functional potential following their injury. This bioengineering approach needs to be extended to accommodate a larger SCI population. This will enable a generalisation of the findings to ensure informed education and training of pressure ulcer prevention for the individual and their carer.

Table of Contents

Table of Contents i
List of Tables v
List of Figures ix
Research Thesis: Declaration of Authorship xvii
Acknowledgements xix
Dissemination xxi
Chapter 1 Background 23
1.1 Motivation 23
1.1.1 Structure of the skin and subcutaneous tissue 23
1.1.2 Definition of pressure ulcer or deep tissue injury 24
1.1.3 Classification of pressure ulcers 25
1.2 Aetiology of pressure ulcers 27
1.3 The role of tissue tolerance, time and friction in pressure ulcer development. 28
1.4 Pressure Ulcers in clinical context and interventions 29
1.4.1 Prevalence rates and incidence 29
1.4.2 Impact of pressure ulcers 32
1.4.3 Risk factors 33
1.4.4 Prevention 35
1.4.5 Spinal cord injury – classification, functional consequences and rehabilitation pathway 36
1.4.6 Prevalence and incidence of pressure ulcers after spinal cord injury 40
1.4.7 Susceptibility and impact of pressure ulcers after spinal cord injury or cauda equina syndrome 41
1.5 Summary 42
Chapter 2 Literature review 43
2.1 Search strategy 43
2.2 Support surfaces and technology 49
2.2.1 Air-based wheelchair cushions 49
2.2.2. Unconventional wheelchair cushions 50
2.2.3 Mattresses 51
2.2.4 Dressing and pads 52
2.2.5 Functional Electrical Stimulation (FES) 53
2.2.6. Summary 53
2.3 Educational and behavioural interventions 54
2.3.1. Self-efficacy 54
2.3.2 Clinician behaviour 55
2.3.3. Computer-based learning 56
2.3.4 Telehealth 56
2.3.5 Summary 56
2.4 Repositioning 57

2.4.1 Tilt and recline 57
2.4.2 Pressure relieving activity 58
2.4.3 Summary 60
2.5 Discussion 60
2.6 Conclusion 61
Chapter 3 A retrospective evaluation of pressure ulcer prevalence after spinal cord injury. 63
3.1 Aims and objectives 64
3.1.1 Aims 64
3.1.2 Objectives 64
3.2 Methods 64
3.2.1 Inclusion criteria 64
3.2.2 Exclusion criteria 65
3.2.3 In-patient data 65
3.2.4 Community Liaison data 65
3.2.5 Statistics 66
3.3 Results 66
3.3.1 Pressure ulcer statistics from inpatients in the Spinal Cord Injury Treatment Centre 66
3.3.2 Location of pressure ulcer 67
3.3.3 Stage of pressure ulcer 69
3.3.4 Severity of injury 70
3.3.5 Level of injury 71
3.3.6 Age 72
3.3.7 Years post injury 74
3.4 Discussion 74
3.5 Conclusion 77
Chapter 4 Material and methods 79
4.1 Research questions 80
4.2 Aims and objectives 80
4.3 Methods 81
4.4 Sample and setting 82
4.4.1 Inclusion criteria: 82
4.4.2 Exclusion criteria: 82
4.4.3 Exclusion criteria for admission to Duke of Cornwall Spinal Treatment Centre: 82
4.4.4 The recruitment process of patients 83
4.5 Material 85
4.6 Test protocols 87
4.6.1 Individualized Pressure Ulcer Prevention Plan 88
4.6.2 Interviews to elicit patient perspectives on barriers and facilitators to use of the IPUPP 89

4.7 Measures 89
4.8 Data analysis 90
4.8.1 Movement to Off-load Vulnerable Areas (MOVA) 90
4.8.2 Statistics 93
4.8.3 Algorithm 93
4.9 Governance and ethical approval 93
Chapter 5 Timepoint 1 results- Initial assessment of posture and mobility in the spinal cord injured inpatient cohort 95
5.1 Participants 95
5.2 Timepoint 1 case studies 98
5.2.1 Participant 5 98
5.2.1.1 Monitoring lying data (night 1) 99
5.2.1.2 Monitoring seating data 105
5.2.2 Participant 9 111
5.2.2.1 Monitoring lying data (night 1) 112
5.2.2.2 Monitiring lying data (night 2) 115
5.2.2.3 Monitoring seating data 118
5.2.3 Participant 3 123
5.2.3.1 Monitoring lying data (night 1) 124
5.2.3.2 Monitoring lying data (night 2) 128
5.2.3.3 Monitoring lying data (night 3) 133
5.3 Analysis of movement profiles 140
5.3.1 Classification based on participant characteristics 140
5.3.2 Movements in the lying position 141
5.3.3 Movements in the sitting position 145
5.4 Development of IPUPP 147
5.5 Skin damage and pressure/movement profiles 148
5.6 Comparison of observed movement vs. predicted movement 149
5.7 Discussion 150
5.8 Summary of key findings 153
Chapter 6 Timepoint 2 results- Analysis of long term pressure monitoring parameters after implementation of individualized pressure ulcer prevention plan 154
6.1 Timepoint 2 case studies 155
6.1.1 Participant 1 155
6.1.2 Participant 4 160
6.1.3 Participant 9 164
6.1.4 Participant 10 168
6.2 Analysis of cohort 171
6.3 Discussion 175
6.4 Summary of key findings 178

Chapter 7 Timepoint 3 results- Long term pressure monitoring in the community setting 180
7.1 Participants 180
7.2 Timepoint 3 Case Studies 181
7.2.1 Participant 5 181
7.2.1.1 Monitoring lying data (night 1) 183
7.2.1.2 Monitoring seating data 186
7.2.2 Participant 11 189
7.2.2.1 Monitoring lying data (night 1) 189
7.2.2.2 Monitoring seating data 193
7.2.3 Participant 13 196
7.2.3.1 Monitoring lying data (night 1) 196
7.2.3.2 Monitoring seating data 201
7.3 Analysis of movement profiles in community settings 205
7.3.1 Movements in the lying position 206
7.3.2 Movements in the sitting position 208
7.4 Discussion 210
7.5 Summary of key findings 214
Chapter 8 Discussion 215
8.1 Achievements in relation to original aims and objectives 215
8.2 Limitations 219
8.3 Novel aspects of the research including advancement in scientific understanding 222
8.4 Future work 229
Appendix 1 Individualised pressure ulcer prevention plans (IPUPP) 231
Appendix 2 Pressure ulcer prevalence collection Sheet (European Pressure Ulcer Advisory Panel 2002) 237
Appendix 3 Interview questions for timepoint 1 and 2 adapted from Integrated Behavioural Model (Montano and Kasprzyk 2015) 239
List of references 240

List of Tables

Table 1.1: Prevalence and incidence data 2000- 2019 (EPUAP,NPUAP,PPPIA. 2019) 31

Table 1.2: International Standards for Neurological Classification of Spinal Cord Injury (ASIA and ISCoS international Standards Commitee 2019)...37

Table 1.3: Muscle grading definition (ASIA and ISCoS international Standards Commitee 2019)38

Table 1.4: Levels of spinal cord injury (Hill Foundation for Families Living With Disabilities 2011)39

Table 2.1: Search terms and criteria for literature review 44

Table 3.1: Phases of inpatient rehabilitation at the Duke of Cornwall Spinal Treatment Centre 63

Table 4.1 Definition of MOVAs...90

Table 5.1: Participant demographics and co-morbidities 95

Table 5.2: Participant support surface and skin specific features at timepoint 1.......................96

Table 5.3: Summary of the monitoring periods during the day and night for each participant during timepoints 1-3...97

Table 5.4: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1...99

Table 5.5: Summary of movements on night 1 of timepoint 1 for P5, as determined by continuous pressure monitoring on foam mattress. 99

Table 5.6: Summary of movement for P5 on day 1 of pressure monitoring on wheelchair cushion. 107

Table 5.7: Summary of movement behaviour for P9 on air mattress and wheelchair cushion at timepoint 1..111

Table 5.8: Summary of movements on night 1 of timepoint 1 for P9, as determined by continuous pressure monitoring on an air mattress. 112

Table 5.9: Summary of movements on night 2 of timepoint 1 for P9, as determined by continuous pressure monitoring on air mattress. 115

Table 5.10: Summary of movement behaviour of P9 on a wheelchair cushion for two days at time point 1...119

Table 5.11: Summary of movement behaviour for P3 on a castellated foam mattress for four nights at time point 1 123

Table 5.12: Summary of movements on night 1 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress 124

Table 5.13: Summary of movements on night 2 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress. 128

Table 5.14 : Summary of movements on night 3 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress 133

Table 5.15: The level of injury and ASIA category for all participants. 140

Table 5.16: Development of IPUPP 148

Table 5.17: Summary of median and range values, corresponding to spinal injury characteristic . Notable trends are highlighted in yellow...152

Table 6.1: Participant demographics and co-morbidities timepoint 2......................................154

Table 6.2: Comparison of movement parameters at timepoints 1 and 2 for P1, as determined by continuous pressure monitoring in both lying position and sitting position. 155

Table 6.3: Summary of movements on day 1 of timepoint 2 for P1, as determined by continuous pressure monitoring on fluid/foam cushion in sitting 156

Table 6.4: Summary of movements. P1, time point 2, night 1 of pressure monitoring- lying. ..158

Table 6.5: Comparison of movements at timepoints 1 and 2 for P4, as determined by continuous pressure monitoring in both lying position and sitting position. 161

Table 6.6: Summary of movements on day 1 of timepoint 2 for P4, as determined by continuous pressure monitoring of foam cushion in sitting. 161

Table 6.7: Comparison of movements at timepoints 1 and 2 for P9, as determined by continuous pressure monitoring in both lying position and sitting position. 164

Table 6.8: Summary of movements on day 1 at timepoint 2 for P9, as determined by continuous pressure monitoring an air mattress in lying. 166

Table 6.9: Comparison of movements at timepoints 1 and 2 for P10, as determined by continuous pressure monitoring in both lying position and sitting position. 168

Table 6.10: Summary of movements on day 1 of timepoint 2 for P10, as determined by continuous pressure monitoring on fluid/foam cushion in sitting. 169

Table 6.11 Descriptive statistics of maximum time between MOVAs for the four participants as estimated from in both lying and sitting positions at timepoints 1 and 2.....172

Table 6.12: The number of postures exceeding three hours between MOVAs for the four participants who were monitored in lying and sitting positions at time points 1 and 2. 175

Table 7.1: Timepoint 3 participant discharge information 180

Table 7.2: Timepoint 3 support surface information 181

Table 7.3: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1..182

Table 7.4: Summary of movement, P5, night 1 of pressure monitoring, timepoint 3...............183

Table 7.5: Sitting data. Standing/walking intervals, P5, day 1 of monitoring, timepoint 3.......186

Table 7.6: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1..189

Table 7.7: Summary of movements for P11, night 1 of pressure monitoring, timepoint 3 190

Table 7.8: Summary of movement behaviour of P13 on foam mattress and wheelchair cushion at time point 3..196

Table 7.9: Summary of movements P13, night 1 of monitoring, timepoint 3...........................199

Table 7.10: Characteristics of patients included in timepoint 3...205

Table 7.11: Summary of median and range values, corresponding to spinal injury characteristic . Notable trends are highlighted in yellow..211

List of Figures

Figure 1.1: Stage 1-4 pressure ulcers (left to right) (Edsberg et al. 2016) 26

Figure 1.2: Unstageable pressure ulcer (left) and DTI (right) (Edsberg et al. 2016) 27

Figure 1.3: The strain-time cell death threshold for Bio-artificial Muscle (BAM) specimens under large compressive strains- adapted from Gefen et al. (2008) published in Oomens et al. (2015)..28

Figure 1.4: Safety thermometer data (National Health Service 2020) 32

Figure 1.5: Factors influencing the susceptibility of an individual for developing pressure ulcers - adapted from Oomens (1985), continuing work by Coleman et al. (2013) produced this modification, which is published in (European Pressure Ulcer Advisory Panel et al. 2019) 34

Figure 2.1: Literature search strategy presented in flow diagram, based on Prisma (2020).......45

Figure 2.2 Litarature map depicting key themes and associated literature, based on an example by Creswell (2009)...47

Figure 3.1: Phase of rehabilitation in which patients initially developed a pressure ulcer. 67

Figure 3.2: Location of pressure ulcer (n=29) acquired in the inpatient cohort..........................68

Figure 3.3: Location of pressure ulcer (n=74) acquired in the outpatient cohort 68

Figure 3.4: Stage of pressure ulcers (n=29) acquired in the in-patient cohort............................69

Figure 3.5: Stage of pressure ulcers (n=74) acquired in the out-patient cohort 69

Figure 3.6: ASIA demographics of in-patient cohort who acquired a pressure ulcer..................70

Figure 3.7: ASIA demographics of outpatient cohort who acquired a pressure ulcer.................70

Figure 3.8: Spinal level of injury of in-patient cohort who acquired a pressure ulcer.................71

Figure 3.9: Spinal level of injury of out-patient cohort who acquired a pressure ulcer 72

Figure 3.10: Age distribution of in-patient cohort who acquired a pressure ulcer 73

Figure 3.11: Age distribution of out-patient cohort who acquired a pressure ulcer...................73

Figure 3.12: Distribution of years post injury of out-patient cohort who acquired a pressure ulcer 74

Figure 4.1: Schematic of recruitment process of patients..84

Figure 4.2.: Foresite PT system to monitor pressures continuously in a bed environment..........86

Figure 4.3: Foresite SS system to monitor pressures continuously in a wheelchair environment86

Figure 4.4: Schematic representation showing three objectives of long-term pressure monitoring 87

Figure 4.5: Schematic outlining process for identifying movement to offload vulnerable areas 92

Figure 5.1 : Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure for P5 at timepoint 1, during the first night of pressure monitoring on a castellated foam mattress..100

Figure 5.2: (A) Pressure scale depicting the pressure values ranging from 0 - 60mmHg. Pressure distributions and corresponding pressure parameters for (B) supine to left side lateral during MOVA 1 (C) Left side lateral to supine during MOVA 2. Magnitude of the four pressure parameters are also indicated. 101

Figure 5.3: Pressure distributions and corresponding pressure parameters for (A) Supine to left lateral during MOVA 3 (B) left side lateral to supine during MOVA 4. Magnitude of the four pressure parameters are also indicated. 102

Figure 5.4: Pressure distributions and corresponding pressure parameters for (A) supine (B) left side lateral (C) supine during MOVA 5. Magnitude of the four pressure parameters are also indicated. 103

Figure 5.5: Pressure distributions and corresponding pressure parameters for (A) Supine (B) sitting up (C) supine during personal care. Magnitude of the four pressure parameters are also indicated...104

Figure 5.6: (A) Pressure scale ranging from 0 – 120 mmHg (B) Pressure distributions in sitting posture for P5. Magnitude of the four pressure parameters are also indicated. 106

Figure 5.7: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of Pressure, column for P5 on day 1 of pressure monitoring on a wheelchair cushion 108

Figure 5.8: Pressure distributions and corresponding pressure parameters at (A) 13:59 (B) 14:09 and (C) 14:15 during MOVA 1. Magnitude of the four pressure parameters are also indicated...109

Figure 5.9: Pressure distributions and corresponding pressure parameters at (A) 18:55 (B) 18:58 and (C) 19:07 during MOVA 2. Magnitude of the four pressure parameters are also indicated...109

113

Figure 5.10: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P9 on T1, night 1 of pressure monitoring on the air mattress.113

Figure 5.11: (A) Pressure scale, ranging from 0 to 60 mmHg. Pressure distributions and corresponding pressure parameters for (B) Right side lateral (C) Left side lateral during MOVA 1. (D) Left side lateral (E) Right side lateral during MOVA 2. Magnitude of the four pressure parameters are also indicated....................114

Figure 5.12: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P9 on T1, night 2 of pressure monitoring on a mattress......116

Figure 5.13: Pressure distributions and corresponding pressure parameters for (A) Right side lateral (B) Left side lateral during MOVA 1. Magnitude of the four pressure parameters are also indicated. 117

Figure 5.14: (A) Pressure legend ranging from 0-120 mmHg. (B) Pressure distributions in sitting posture of P9. Magnitude of the four pressure parameters are also indicated.118

120

Figure 5.15: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of pressure, column for P9 on T1, day 1 of pressure monitoring on a wheelchair cushion. 120

Figure 5.16: Pressure distributions and corresponding pressure parameters at (A) 14:41 (B) 14:47 and (C) 15:05 during MOVA 1. Magnitude of the four pressure parameters are also indicated...121

Figure 5.17: Pressure distributions and corresponding pressure parameters at (A) 18:31 (B) 18:34 and (C) 18:39 during MOVA 2. Magnitude of the four pressure parameters are also indicated...121

Figure 5.18: Temporal profiles of (A) Temporal profiles (B) Contact Area (C) Centre of Pressure, row, and column, for P3 on night 1 of pressure monitoring on a foam mattress 125

Figure 5.19: (A) Pressure scale from 0 – 60mmHg. Pressure distributions and corresponding pressure for B) Right side lateral (C) left side lateral during MOVA 1. Magnitude of the four pressure parameters are also indicated. 126

Figure 5.20: Pressure disributions and corresponding pressure parameters for (A) Left side lateral (B) Right side lateral during MOVA 2 and (C) right side lateral (D) during personal care. Magnitude of the four pressure parameters are also indicated...........127

Figure 5.21: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column, for P3 on night 2 of pressure monitoring on a mattress...........129

Figure 5.22: Pressure distributions and correpsonding pressure parameters for (A) Right side lateral (B) left side running man during MOVA 1 and (C) left side running man (D) Right side running during MOVA 2. Magnitude of the four pressure parameters are also indicated..130

Figure 5.23: Pressure distributions and corresponding pressure parameters for (A) Right side running man and (B) Left side running man during MOVA 3 (C) Left side running man (D) Left side running man during MOVA 4. Magnitude of the four pressure parameters are also indicated...131

Figure 5.24: Pressure distribution and corresponding pressure parameters for (A) Left side running man (B) a repositioned left side running man during MOVA 5. Magnitude of the four pressure parameters are also indicated...132

Figure 5.25: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P3 on night 3 of pressure monitoring on a mattress............134

Figure 5.26 : Pressure distributions and corresponding pressure parameters on (A) Left side running man and (B) Right side running man during MOVA 1 and (C) Right side running man (D) Left side running man during MOVA 2. Magnitude of the four pressure parameters are also indicated. 135

Figure 5.27: Pressure distributions and corresponding pressure parameters for (A) Left side running man (B) Right side lateral during MOVA 3 (C) Right side lateral (D) Left side lateral during MOVA 4. Magnitude of the four pressure parameters are also indicated. 136

Figure 5.28: Pressure distributions and corresponding pressure parameters for (A) Left side lateral (B) Right side lateral during MOVA 5. Magnitude of the four pressure parameters are also indicated..137

Figure 5.29: Histogram of maximum interval between MOVA in lying position with reference to ASIA - clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 141

Figure 5.30: Histogram of average number of MOVA in lying position with reference to ASIA - clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 142

Figure 5.31: Histogram of average number of MOVAs per hour in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 143

Figure 5.32: Histogram of maximum interval between MOVAs in the lying position with reference to the level of injury of the participants- clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 143

Figure 5.33: The algorithm prediction of average number of MOVAs in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 144

Figure 5.34: The algorithm prediction of the maximum interval between MOVAs in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 144

Figure 5.35: Histogram of average number of MOVAs in the sitting position for each ASIA type, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 145

Figure 5.36: Histogram of maximum interval between MOVA in the sitting position for each ASIA type, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 146

Figure 5.37: Histogram of average number of MOVA in sitting position with reference to spinal level of injury, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 146

Figure 5.38: Histogram of the maximum interval between MOVAs in sitting position with reference to spinal level of injury, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 147

Figure 6.1: Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure row and (D) Centre of pressure column for P1 at timepoint 2, during the first day of pressure monitoring on a fluid-foam cushion while sitting. 157

Figure 6.2: Temporal profiles of (A) Contact Area and (B) Centre of Pressure row and column for P1 at timepoint 2, during the first day of pressure monitoring on an air mattress while lying...159

Figure 6.3: Temporal profiles of (A) Centre of Pressure row and (B) Centre of pressure -column for P4 at timepoint 2, during the first day of pressure monitoring on a foam cushion while sitting 162

Figure 6.4: Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure row for P9 at timepoint 2, during the first day of pressure monitoring on a fluid-air cushion while sitting. 165

Figure 6.5: Temporal profiles of Centre of Pressure row and column for P9 at timepoint 2, during the first night of pressure monitoring on an air mattress in lying. 167

Figure 6.6: Temporal profiles of (A) Contact Area (B) Centre of Pressure column (C) Centre of Pressure, row for P10 at timepoint 2, during day 1 of pressure monitoring whilst sitting. 170

Figure 6.7: Hourly distribution of the times between MOVAs during lying at timepoint 1 and timepoint 2 for participants (A) P1, (B) P4, (C) P9 and (D) P..........................173

Figure 6.8: Hourly distribution of the times between MOVAs during sitting at timepoint 1 and timepoint 2 for participants (A) P1, (B) P4, (C) P9 and (D) P10.....................174

Figure 6.9: Pressure distributions of P4 in the sitting position showing pelvic obliquity to the left side in (A) Timepoint 1 (B) Timepoint 2...177

Figure 6.10: Pressure distributions of P9 in the sitting position showing pelvic obliquity to the left side in (A) Timepoint 1 (B) Timepoint 2...177

Figure 6.11: Pressure distributions of P10 in the sitting position indicating leaning towards the left trochanter (A) Timepoint 1 (B) Timepoint 2...177

Figure 7.1 Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row and column for P5 at timepoint 3, night 1 of pressure monitoring on mattress..184

Figure 7.2: (A) pressure scale ranging from 5-120mmHg. Pressure distribution and corresponding pressure parameters on (B) right side lateral to supine during MOVA 1. (C) Supine to left side lateral during MOVA 2,P5, timepoint 3, night 1 of mattress monitoring 185

Figure 7.3: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of Pressure, column for P5 at timepoint 3, night 1 of pressure monitoring on mattress. 187

Figure 7.4: (A) Pressure scale ranging from 0 – 120 mmHg. Distribution of pressures and corresponding pressure values in sitting position after each walk standing/interval at (A) 12:05:06 (B) 14:03:14 (C) 15:02:05 p5, timepoint 3, day 1 188

Figure 7.5: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) centre of pressure column for P11 on timepoint 3, night 1 of pressure monitoring on mattress..191

Figure 7.6: (A) Pressure scale ranging from 0 – 60mmHg. Pressure distributions and corresponding pressure parameters for (B) right side lateral (C) left side lateral during MOVA 1. 192

Figure 7.7: Histogram of peak pressure for P11, (A) night 1 of monitoring, timepoint 1 (B) night 1 of monitoring, timepoint 3...192

Figure 7.8: Temporal profiles of (A) peak pressure (B) contact area (C) centre of pressure, row (D) centre of pressure column for P11 on T3, day 1 of pressure monitoring on wheelchair cushion 194

Figure 7.9: Pressure scale ranging from 0 – 120 mmHg,Pressure distributions and corresponding pressure parameters for sitting postures at two hourly intervals (B) 11:00 (C) 13:00 and (D) 15:00 for P11, day 1 of monitoring, timepoint 3. 195

Figure 7.10: (A) Pressure scale ranging from 0 – 60mmHg. Pressure distributions and corresponding pressure parameters for P13 (B) right side lateral (C) left side lateral (D) left side lateral for MOVA 1 198

Figure 7.11: Pressure distributions and corresponding pressure parameters for p13 which depicts repositioning on lateral turning system from (A) Supine (B) Left side lateral for MOVA 1, night 1, timepoint 3 199

Figure 7.12: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) centre of pressure, column for P13 at timepoint 3, night 1 of pressure monitoring on mattress and lateral turning system.. 200

Figure 7.13: Temporal profiles of (a) Peak pressure (b) Contact Area (c) Centre of Pressure, row (d) centre of pressure column for P13 at timepoint 3, day 1 of pressure monitoring on wheelchair cushion 202

Figure 7.14: (A) Pressure scale ranging from 0 – 120 mmHg. Pressure distributions and corresponding pressure parameters for sitting postures at two hourly intervals (B) 15:00 (C) 17:00 (D) 19:00, P13, day 1, timepoint 3 203

Figure 7.15: Clinical estimation of average number of MOVAs in lying position with respect to spinal level of injury of the participants at timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 206

Figure 7.16: The clinical estimation of maximum interval between MOVAs in lying position with respect to level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 206

Figure 7.17: Clinical estimation of average number of MOVAs in lying position with respect to ASIA score of the participants at timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars 207

Figure 7.18: The clinical estimation of maximum interval between MOVAs in lying position with respect to ASIA score, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 207

Figure 7.19: The clinical estimation of Frequency of MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 208

Figure 7.20: The clinical estimation of maximum interval between MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 209

Figure 7.21: The clinical estimation of maximum interval between MOVAs in sitting position with respect to ASIA score, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars. 209

Figure 7.22: The clinical estimation of maximum interval between MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.210

Figure 8.1 Image demonstrating elevated peak pressures due to creases in mattress CPM mat.221

Figure 8.2: Average number of MOVAs, timepoint 1 2 3 (A) P1 (B) P4 224

Figure 8.3 Schematic representing key intervention stages, information which instructed each stage of the intervention and future work..228

Research Thesis: Declaration of Authorship

Print name: Sarah Louise Fryer

Title of thesis: Long-term monitoring of persons with spinal cord injury (SCI): implication for pressure ulcer development

I declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:-

Caggiari S, Worsley PR, Fryer SL, Mace J and Bader DL (2021) Detection of posture and mobility in individuals at risk of developing pressure ulcers. *Medical Engineering & Physics* 91: 39-47

Signature: .... Date: 19th July 2022

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Dissemination

Publication

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Fryer SL, Caggiari S, Major D, Bader DL, Worsley PR (2021) **Continuous pressure monitoring of inpatient spinal cord injured patients: Implications for Pressure Ulcer Development-** submitted for review to *Spinal Cord*

Conference Presentation

Fryer SL (2019) Retrospective Evaluation of Pressure Ulcers After Spinal Cord Injury. The 36th GUTTMANN Conference 27th-28th June , Belfast

Conference Poster

Fryer SL (2019) Developing individualized pressure ulcer prevention plans for spinal cord injured using pressure monitoring technologies European Pressure Ulcers Advisory Panel (EPUAP), 18-20 September, Lyon.

Chapter 1 Background

1.1 Motivation

Pressure ulcers (PUs) are known to be detrimental to both the physical and mental health of affected individuals and their carers. In addition, they represent a large financial burden to healthcare providers. They affect a wide range of individuals of various ages. There are a number of factors that make an individual who has sustained an spinal cord injury (SCI) or cauda equina syndrome (CES) vulnerable to PUs. These include a lack of mobility, reduced sensation and prolonged activities supported in chairs and beds, where soft tissues are exposed to potentially harmful mechanical loading conditions. The SCI/CES population encompasses individuals of various ages, social backgrounds and co-morbidities. Their physical and psychological symptoms also vary depending on the level and severity of spinal injury. These factors will inevitably provide challenges when monitoring specific interventions designed to prevent PUs. The rationale for the current research study is there is little understanding of how monitoring technologies can support the identification of persons with spinal cord injury (PWSCI) who are most at risk of pressure ulcers. Further research is required to determine how feasible it is to use these technologies to inform and support individualized pressure ulcer prevention plans (IPUPPs) in this distinct patient group. Additionally, there is no current evidence to demonstrate the ways in which posture and mobility change in the transfer from acute to community settings. It is also essential to explore whether technology can be utilized to promote preventative strategies post discharge and longer term.

The following sections include a general introduction followed by the aetiology and pathophysiology of pressure ulcers with particular focus on the SCI and CES populations.

1.1.1 Structure of the skin and subcutaneous tissue

Bouten et al. (2003) identified a need to incorporate all soft tissue layers in the study of PUs, namely, the epidermis and dermis compromising the skin, subcutaneous tissues including fat, fascia and deep muscle layers.

As the largest organ of the body, the skin is responsible for many important functions. Crucially, the skin allows gas and fluid exchange across its surface and maintains internal body homeostasis via the activity of sweat glands and blood vessels. Other functions include the protection of underlying tissues and organs, excretion, immunity and the synthesis of vitamin D (Pasparakis et al. 2014)

The structure of the skin is divided into three separate layers, namely, the epidermis, the dermis and the subcutaneous tissue. The outermost layer, the epidermis, contains many essential cells and is divided into 5 strata. Within the deepest region of the strata, *keratinocytes*, the most predominant cell, proliferate and slowly progress outwards through the skin surface. The uppermost superficial layer of the epidermis, termed the stratum corneum, contains 15 to 20 layers of cells called *corneocytes*. These represent dead, annucleated cells which are vital in maintaining transport and barrier properties of the skin. Others significant cells include *melanocy*tes which produce the colour pigment, melanin, *Langerhan cells* responsible for the immune response and *Merkel cells,* which provide tactile sensation . The epidermis is connected to the dermis by an undulating structure, the epidermal-dermal junction, whose integrity is vital for efficient transport and communication between the two layers (Briggaman and Wheeler 1975).

The epidermis is connected to the dermis by an undulating structure, the dermal-epidermal junction. The dermis contains many structures which are critical in maintaining homeostasis and protective features. These include blood and lymphatic vessels, nerve endings, hair follicles, sebaceous glands and sweat glands. Within the dermis are *fibroblasts*, which are essential cells in providing the structural framework of healthy tissue and in wound healing. They produce extracellular matrix components, collagen, elastin and hydrophilic proteoglycans (Bader and Worsley 2018). The subcutaneous tissue is a protective, insulating layer which is loosely connected to the dermis. The adipose-rich tissue facilitates movement and supports dense vessel and nerve networks within the tissue. This layer also serves to absorb mechanical shock to underlying structures, shape the external features of the organism, and regulate temperature (Diegel et al. 2013).

Damage to the skin and underlying tissue, caused by external or intrinsic factors, can result in a PU or, in a few cases, a deep tissue injury (DTI). In the latter case, initiation occurs subcutaneously in skeletal muscles, tissues important in roles involving locomotion, oxygen consumption and substrate turnover (Rivas and Fielding 2013).

1.1.2 Definition of pressure ulcer or deep tissue injury

A PU, also known as a bed sore, pressure sore, pressure injury or decubitus ulcer has been defined by international consensus as a 'localized injury to the skin and/or underlying tissue, as a result of pressure, or pressure in combination with shear " (EPUAP,NPUAP,PPPIA.2019). Pressure ulcers usually occur over a bony prominence, but can also occur over other tissue sites exposed to mechanical loading via a functional medical device. The vast majority of PUs are detected via breakdown of skin tissues. However a separate type, termed a DTI, originates in subcutaneous muscle tissue. These injuries are the result of intense and/or prolonged pressure and shear forces at the bone-muscle interface. These injures are particularly difficult to detect at an early stage as pressure-related damage occurs under intact skin. A DTI can be defined as “Purple or maroon localized area of discoloured intact skin or blood-filled blister due to the damage of underlying soft tissue from pressure and/or shear. The area may be preceded by tissue that is painful, firm, mushy, boggy, warmer or cooler, as compared to adjacent tissue”. In addition, a definition for mucosal membrane pressure injury has been specified. Mucosal pressure injuries are “primarily related to medical devices, typically caused by tubes and/or their stabilization equipment exerting sustained compressive and shear forces on the vulnerable mucosa and underlying tissues” (EPUAP,NPUAP,PPPIA. 2019). All such injuries can present serious consequences in terms of physical and mental health.

1.1.3 Classification of pressure ulcers

In order to classify pressure ulcers, a numerical staging system is widely used by clinicians. This staging system refers predominantly to the depth of the lesion, while other factors such as presence of slough may also be considered. This international staging system was updated via consensus meeting and published in Edsberg et al. (2016). After significant local debate in the US, the authors has renamed the condition as pressure injury (PI), which is also the term used in the Pan-Pacific region. However, European healthcare and research institutes are not in agreement with this change and continue to describe the condition as a pressure ulcer (PU). They essentially describe the same event of skin damage. Throughout this thesis, the term PU will be used. Its classification ranges from stages 1-4, with two further categories for unstageable PUs and DTI, as described below and illustrated in Figures 1.1 and 1.2 (Edsberg et al. 2016).

Stage 1: Non-blanchable erythema of intact skin

Intact skin with a localized area of non-blanchable erythema, which may appear differently in darkly pigmented skin. Presence of blanchable erythema or changes in sensation, temperature or firmness may precede visual skin changes. Color changes do not include purple or maroon discoloration, as these are more likely to indicate deep tissue injury.

Stage 2: Partial-thickness skin loss with exposed dermis

Partial-thickness loss of skin with exposed dermis. The wound bed is viable, pink or red, moist, and may also present as an intact or ruptured serum-filled blister. Neither adipose (fat) nor deeper tissues are visible in the ulcer. Granulation tissue, slough and eschar are also not present. This stage should not be used to describe moisture associated skin damage (MASD) including incontinence associated dermatitis (IAD), intertriginous dermatitis (ITD), medical adhesive-related skin injury (MARSI), or traumatic wounds (skin tears, burns, abrasions).

Stage 3: Full-thickness skin loss

Full-thickness loss of skin, in which adipose tissue is visible in the ulcer and granulation tissue and epibole (rolled wound edges) are often present. Slough and/or eschar may be visible. The depth of tissue damage varies by anatomical location with, for example, areas with significant adipose tissue developing deeper wounds. Undermining and tunneling may occur. Fascia, muscle, tendon, ligament, cartilage and/or bone are not generally exposed. If slough or eschar obscures the extent of tissue loss this is classified as an unstageable ulcer.

Stage 4: Full-thickness skin and tissue loss

Full-thickness skin and tissue loss with exposed or directly palpable fascia, muscle, tendon, ligament, cartilage or bone in the ulcer. Slough and/or eschar may be visible. Epibole (rolled edges), undermining and/or tunneling are often evident. Depth varies by anatomical location. If slough or eschar obscures the extent of tissue loss this is classified as an unstageable pressure ulcer.

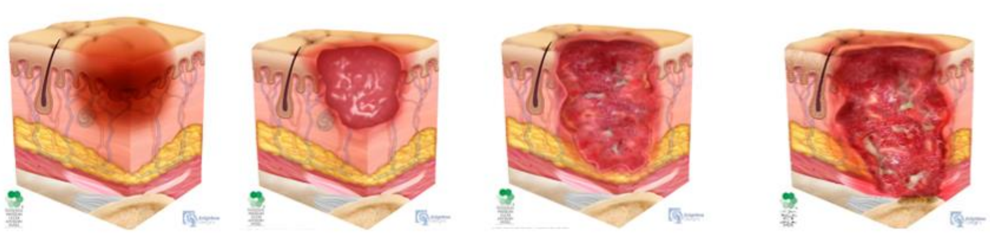


Figure 1.1: Stage 1-4 pressure ulcers (left to right) (Edsberg et al. 2016)

Unstageable: Obscured full-thickness skin and tissue loss

Full-thickness skin and tissue loss in which the extent of tissue damage within the ulcer cannot be confirmed because it is obscured by slough or eschar. If slough or eschar is removed, a Stage 3 or Stage 4 pressure ulcer could be revealed. Stable eschar, characterised as dry, adherent, and intact without erythema or fluctuance, on the heel or ischemic limb should not be softened or removed.

Deep Tissue Injury: Persistent non-blanchable deep red, maroon or purple discoloration

Intact or non-intact skin with localized areas of persistent non-blanchable deep red, maroon, purple discoloration or epidermal separation revealing a dark wound bed or blood-filled blister. Pain and temperature change often precede skin color changes. Discoloration may appear differently in darkly pigmented skin. The wound may evolve rapidly to reveal the actual extent of tissue damage but can also resolve without further tissue loss. If necrotic tissue, subcutaneous tissue, granulation tissue, fascia, muscle or other underlying structures are visible, this indicates a full thickness pressure ulcer, which may be classified as Stage 3, Stage 4 or Unstageable.

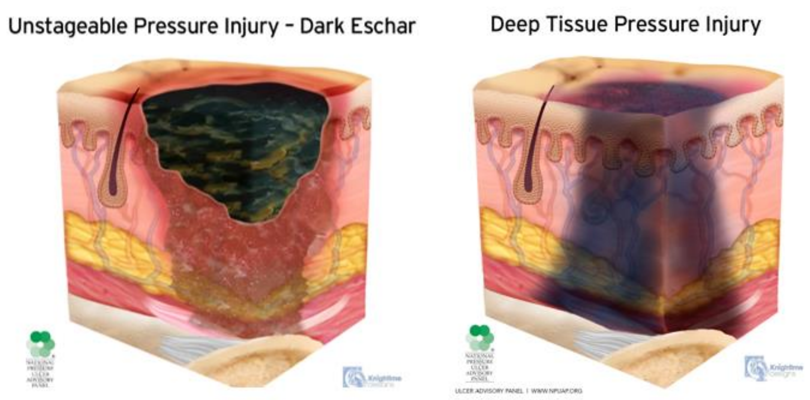


Figure 1.2: Unstageable pressure ulcer (left) and DTI (right) (Edsberg et al. 2016)

1.2 Aetiology of pressure ulcers

The aetiopathogenesis of PUs has long been considered to involve the obstruction of blood vessels within loaded soft tissues leading to *pressure-induced ischemia*. This mechanism will result in a limited delivery of vital nutrients, such as oxygen, to the cell niche. The resulting cell death would restrict any remodelling processes and lead to the accumulation of soft tissue breakdown. In the last two decades other mechanisms have been clarified (Bouten et al., 2003), using bioengineering techniques involving a range of cell-based studies (Gawlitta et al., 2007), tissue and animal models (Ceelen et al. 2008) and human studies. Accordingly, it is now recognised that, in addition to pressure-induced ischaemia, pressure ulcers can result from the following mechanisms namely:

• ***Impaired interstitial and lymphatic flow*** – this will result in an accumulation of toxic intercellular waste products, which are both damaging to the cells and can influence the local cellular environment e.g. reduced levels of local pH. The development of non-invasive techniques has enabled this mechanism to be recently investigated in humans (Gray et al., 2016)

• ***Ischaemia-reperfusion injury*** associated with load removal – this results in the reperfusion of blood and transport of other nutrients, which may result in an over production and release of oxygen-derived free radicals, which are known to be damaging to many tissues and organs. These effects have been demonstrated using animal models (Pierce et al., 2000; Unal et al., 2001).

Cell and tissue deformation – tissue deformation triggers a variety of effects, which may be involved in early cell damage, such as local stresses leading to buckling and rupture of the membrane (Loerakker et al. 2011). This loss of membrane integrity will lead to altered transport of biomolecules and ions, volume changes and modifications of cytoskeletal organisation, all of which can affect cell viability and limit the remodelling capacity of the tissues (Nelissen et al. 2018).

1.3 The role of tissue tolerance, time and friction in pressure ulcer development.

Seminal work from Reswick and Rogers in the 1970's established a relationship between the magnitude and time of external pressure and the maintenance of cell/tissue viability. This was subsequently modified by Gefen et al. (2008) to form the current relationship, which is illustrated in the form of a strain-time curve in Figure 1.3.

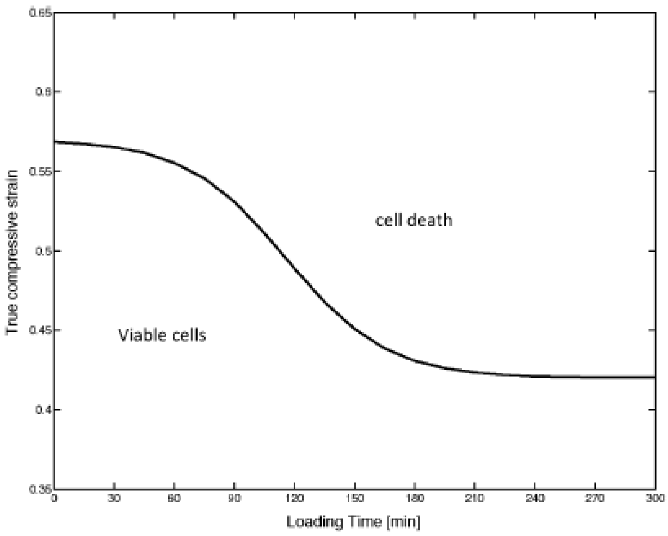


Figure 1.3: The strain-time cell death threshold for Bio-artificial Muscle (BAM) specimens under large compressive strains- adapted from Gefen et al. (2008) published in Oomens et al. (2015)

This relationship inevitably depends on the tolerance of the individual, which is influenced by a wide range of factors such as co-morbidities, nutrition and circulatory issues.

It is also known that friction is a factor in tissue breakdown, as it can lead to increased internal shear stresses and strains. The coefficient of friction represents a measure of the amount of friction existing between two contacting surfaces, which is dependent upon the contact surface materials and their topography, the surface moisture and ambient humidity. Indeed, there is an increase in the coefficient of friction when the skin or the support surface is wet and/or the skin is macerated (Carville 2007; Reger et al. 2010). This situation can typically occur when individuals present with incontinence or sweat excessively. Movement to overcome increased friction will result in shear forces, which also contribute to the breakdown of vulnerable skin tissue. Increasingly, it is evidenced that microclimate affects the vulnerability of the skin. Indeed, increases in humidity and temperature can result in more permeable skin with a compromised stiffness and strength. It is interesting to note that overtly dry skin can also become fragile and more likely to breakdown (Xing et al. 2006; Reger et al. 2007). It was identified by Kottner et al. (2018) that individual intrinsic characteristics can make patients more vulnerable to microclimate effects

It is well established that, in a clinical context, it is essential to minimize the local tissue deformation by distributing pressures uniformly over a support surface (Bader and Worsley 2018). Advanced bioengineering studies involving MRI and finite element modelling have demonstrated when sitting, maximal tissue strains and stresses occur in the gluteal muscles, as opposed to the fat or skin tissues adjacent to the body–seat interface (Oomens et al. 2015). This explains the risk of DTI development in prolonged sitting, particularly associated with individuals with muscle atrophy e.g. SCI.

1.4 Pressure Ulcers in clinical context and interventions

1.4.1 Prevalence rates and incidence

Various methods of design have been used to analyse either the prevalance or incidence of PUs , both in community and hospital settings. This makes it problematic to make direct comparison between studies. Table 1.1 summarises PU prevalence and incidence data from the period 2000-2019, as published in the recent Interantional Guidelines (EPUAP,NPUAP,PPPIA 2019). Pressure ulcer prevalance is the proportion of individuals within a defined population i.e. individuals within a specific geographic region, facility or ward, that have a recorded pressure ulcer at a defined perıond of time. By contrast, Facility Acquired Pressure Injuries or Ulcers (FAPI) rates estimate the number of individuals with pressure ulcers at a specific point that were acquired within a given facility. This latter parameter is particularly relevant when assesing the effectiveness of PU prevention programmes. The estimation presented in Table 1.1 is based on prevalance rates that included stage 1 PUs and in which trained observers conducted skin assesments.

In order to ascertain prevalence and incidence rates in the acute care setting, Tubaishat et al. (2018) study utilised a meta-analysis This analysis included ten studies which used the EPUAP classification system. These studies studies reported prevalance rates from 3.4% to 20.3%. Eight of the included studies used used the NPUAP classification system. These studies reported prevlance rates from 6% to 22%. .

Chaboyer et al. (2018) conducted a meta-analysis of pressure data from 10 studies which investigated critical care settings, internationally. The majority of these studies (70% of the incidence studies and 100% of the prevalance studies) reported that PUs were identified by skin inspections. The rates of both prevalance and incidence are comparably higher to those in acute care, with the 95% confidence interval (CI) at 10-25.9%.

Few prevalance and incidence studies conducted in peadiatric populations are reported in the literature. However two of the more recent studies have investigated large populations . Razmus and Bergquist-Beringer (2017) studied 678 peaditatric facilities in the US and Sánchez-Lorente et al. (2018) studied 65,359 indivdiuals in Spanish healthcare settings. For hospitialized children medical device related PUs remain a sigificnant issue, with one study reporting 84% of PUs to be associated with a medical device (Schlüer et al. 2009).

The largest and most recent study used to estimate prevelance and incidence in older persons care is a population based study based in Japan. The data for this study was derived from a mandatory public database containing records for all individuals receiving community or facility based care. The rate of PUs was 20.3 per 1000 population for those aged 65 or over. This increases to 44.6 per 1000 population in those aged 80 years or over. Both of these figures are substantially higher than in the population aged 18-64 years , where 9.2 per 1000 population developed PUs (Nakashima et al. 2018).

Table 1.1: Prevalence and incidence data 2000- 2019 (EPUAP,NPUAP,PPPIA. 2019)

Setting or Population	Prevalence Rates	Incidence/FAPI Rates
Acute	6 % to 18.5% (Tubaishat et al. 2018)	0% to 12% (Bales and Padwojski 2009)
Critical	95% CI: 10.0 to 25.9% (Chaboyer et al. 2018)	95% CI: 16.9 to 23.8% (Chaboyer et al. 2018)
Aged Care	4.1% (Wilborn et al. 2010) to 32.2% (Abel et al. 2005)	1.9% (Igarashi et al. 2013) to 59% (Brienza et al. 2001)
Pediatric care		
• Primary health care	• 1.75% (95% CI: 1.71 to 1.73) (Sánchez-Lorente et al. 2018)	
• General acute care	• 1.8% to 4.0% (Pellegrino et al. 2017)	• 0.57% (Razmus and Bergquist-Beringer 2017) to 21.4% (Pellegrino et al. 2017)
• Critical care	• 32.8% (Pellegrino et al. 2017)	• 0.25% (Murdoch 2002) to 27% (Curley et al. 2003)
• Mixed settings	• 0.47% (Baldwin 2002) to 7.1% (Pellegrino et al. 2017)	• 0.29% (Baldwin 2002) to 27.7% (Schlüer et al. 2009)
Operating room	-	5% (Connor et al. 2010) to 53.4% (Schuurman et al. 2009)

A further systematic review which looked at PU prevalence rates in Europe, this review included stage 1 PUs . The median prevalence rate identified was 10.8% (standard deviation: 7%; range: 4.6-27.2%). The highest PU prevalence reported was from the Netherlands (27.2%; n=17,494 participants), and the lowest was reported from Finland (4.6%; n=629 participants). Almost 32.4% (n=151,195) of the PUs were category I and the most common site for PUs was the sacrum (Moore et al. 2019).

In the UK, The UK National Health Service (NHS) "Safety Thermometer" was introduced with the aim of reporting incidence rates of harm, including Stage 2-4 PUs, in all care settings. It is, however, highly dependent on the efficiency of staff reporting consistently in various settings. Figure 1.4 illustrates point prevalence data that has been recorded over a 7 year period via the NHS safety thermometer. Although there was a gradual decreasing trend in the PU prevalence rates from 2012 to the end of 2017, subsequently this trend reversed with a prevalence rate of 4.8% in the latest data from February 2020. This demonstrates there is still a clear need for further clinical investigation and innovation in this area (National Health Service 2020). Safety thermometer data collection was suspended in March 2020, after the COVID 19 pandemic.

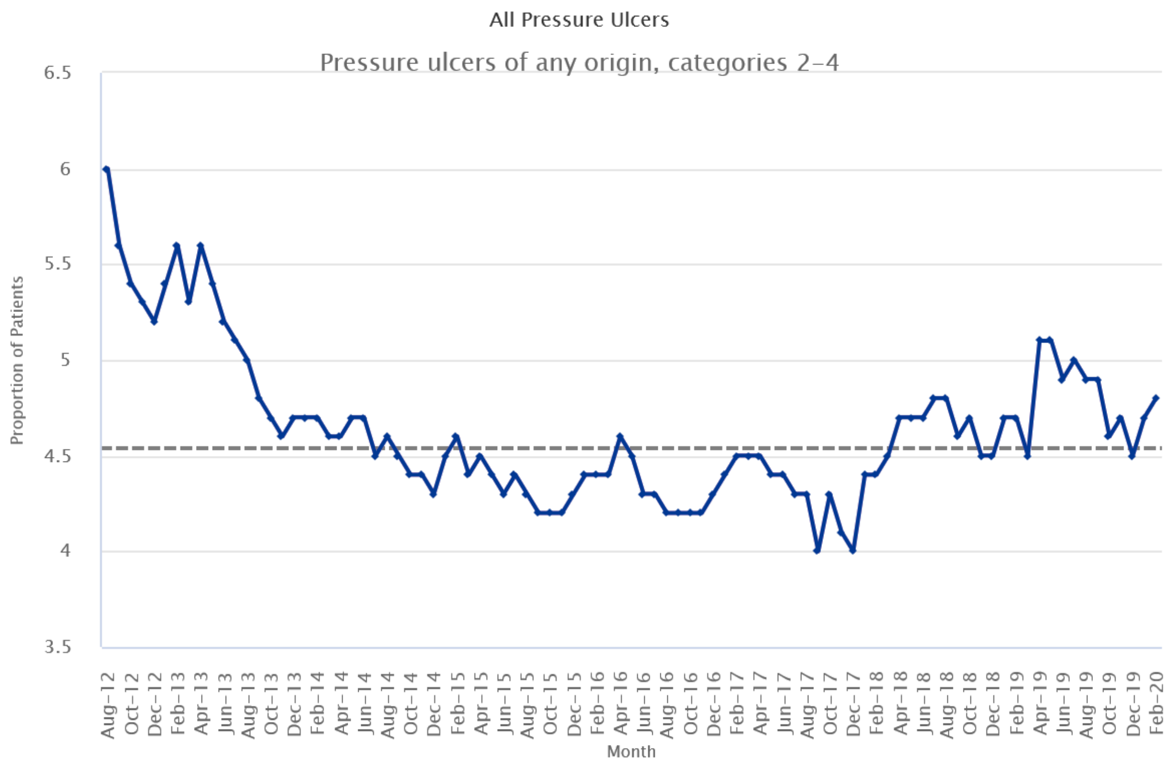


Figure 1.4: Safety thermometer data (National Health Service 2020)

1.4.2 Impact of pressure ulcers

Qualitative studies have explored how skin damage can affect the day-to-day lifestyle of an individual. Pain is one of the most common issues to be identified in the literature, with descriptions often including “out of control” and “insurmountable”. PUs can also create anxiety about the future, with variable prognosis of healing and future quality of life (Jackson et al. 2017).

A systematic review placed impacts into four themes, namely, physical impact, social impact, physiological impact and other impacts. Physical impacts included difficulty to complete activities of daily living (ADLS) due to being restricted to the bed or chair. The appropriate treatments were intrusive and burdensome in terms of daily life. Psychological impacts included changes in body image and self-concept. A desire to regain and retain independence also featured prominently in this category. Social impact included isolation and confinement associated with the burden of PU treatments. Hospitalization for PU treatment in particular was identified as problematic in personal relationships. This was due to limitations in intimacy and sexual relations. Other impacts related to feeling overly dependent on others and the perceived impact of the PU on the latter (Gorecki et al. 2009).

It has also been reported that PUs interfered with sleep and appetite (Gorecki et al. 2011). This review also revealed individuals experiencing social anxiety and distress, due to the smell and appearance of PUs. Indeed, the overall psychological effects of PUs are not always well managed by health care professionals (Hopkins et al. 2006a; Spilsbury et al. 2007; Gorecki et al. 2011).

Guest et al. (2015) conducted a retrospective cohort analysis of the records of patients in "The Health Improvement Network" (THIN) Database. A total of 1000 adult patients, who presented with a chronic wound in 2012/2013 were randomly selected and matched with 1000 control patients with no history of a wound. Patient characteristics, wound-related health outcomes and all healthcare resource use were quantified and the total NHS cost of patient management was estimated at 2013/2014 prices. The total annual cost of PUs was estimated to be between £507 and £530 million. A more recent study indicated the number of new PUs in the UK was estimated to have increased to 200,000 in 2017/2018 and this burden was predicted to cost the NHS £1.74 billion (Guest et al. 2018; Guest et al. 2020). Considering the current pressures on the NHS, and difficulties predicted for the future in the post COVID 19 pandemic phase, reduction of this expensive and largely preventable aspect of fundamental care must represent a critical goal. This is the case for health services worldwide.

The cost of treating PUs identified through a retrospective study in Ireland revealed values ranging from €1195-4531 (Reilly et al. 2021). However, this was based on a small sample of community wounds (n=20).

1.4.3 Risk factors

In terms of identifying PU risk in the general population, a wide range of intrinsic and extrinsic factors have commonly been associated with PU development. An international expert group, identified severe restrictions in mobility, and perfusion issues (including diabetes) as primary conditions indicative of an individual at high risk of developing a PU, as written by Coleman et al. (2014). This work also recognizes a strong association between the presence of non-blanching erythema (stage 1 PU) and the development of subsequent stage 2, 3 and 4 PUs. In recent international guidelines, high risk individuals are specified as:

- Older adults,

- Individuals who have experienced trauma
- Individuals with SCI or CES
- Individuals who have sustained a fractured hip
- Individuals in nursing homes or community care,
- Individuals who are have become acutely ill
- Individuals with diabetes
- Individuals and critical care settings

Risk factors arise from both the mechanical boundary conditions, associated with the type, magnitude and time period of applied loading, and the susceptibility and tolerance of the individual (EPUAP/NPIAP/PPPIA, 2019). The latter is associated with the mechanical and thermal properties of the tissues, their geometry, physiology and repair potential (Figure 1.5).

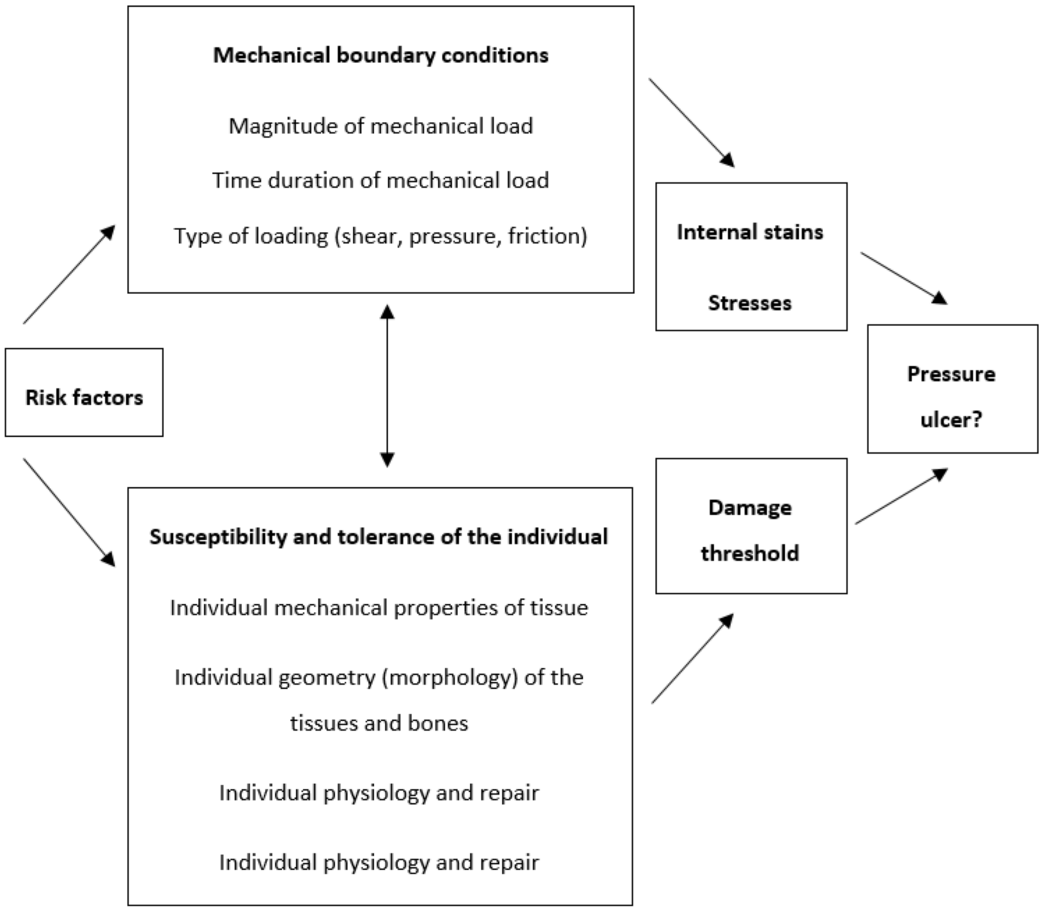


Figure 1.5: Factors influencing the susceptibility of an individual for developing pressure ulcers - adapted from Oomens (1985), continuing work by Coleman et al. (2013) produced this modification, which is published in (European Pressure Ulcer Advisory Panel et al. 2019)

There are a variety of risk assessment scales to assess individuals that are currently used predominantly by nurses in clinical practice. The most common examples used in the UK include the Braden Scale (Bergstrom et al. 1987) and the Waterlow Scale (Waterlow 1985). These scales are intended to be a precursor to PU prevention care planning and interventions. However, there is significant debate about the effectiveness of use of these risk assessment scales in the clinical environment. For example, Johansen et al. (2014) reported that the use of formal risk assessment scales did not appear to have a significant effect on subsequent care planning. A specific PU risk assessment scale for PWSCI, termed SCIPUS, was developed by Salzberg et al. (1996). However, studies have found the SCIPUS has not proved superior to other generic PU risk assessment scales, in terms of early identification of individuals who go on to develop PUs, particularly in acute inpatient admissions (Delparte et al. 2015; Krishnan et al. 2016). Mortenson et al. (2008) reported that the Braden scale has the best-combined validity and utility evidence for a SCI cohort. While risk assessment scales provide a standardised approach, to determine risk factors in terms of PU development, it has been recommended that they be used in combination with clinical judgement to identify appropriate prevention strategies (Moore and Patton 2019)

1.4.4 Prevention

Recommended interventions for the prevention and treatment of PUs predominantly involve individual risk assessment, repositioning and pressure redistributing support surfaces. The established clinical adopted repositioning technique for bed-bound individuals involves a 30^o side-lying position with a 30^o to 45^o backrest elevation (Moore et al. 2011). There has been significant debate surrounding the frequency of repositioning. For example, Defloor et al. (2005) reported that turning an individual every four hours on viscoelastic foam mattresses resulted in significantly fewer pressure ulcers , compared to turning every two or three hours on a non-pressure redistributing mattress. However, a recent systematic review by Gillespie et al. (2020) suggests there is limited evidence to support 2 hourly repositioning. This review also suggests that 3-4 hourly repositioning is more cost effective in terms of nursing time.

The guidelines surrounding support surfaces suggest individual decisions should be based on the risk assessment tools, including the Braden and Waterlow. Reactive support surfaces, based on foam, are recommended for individuals deemed to be at low or moderate risk of PUs. These surfaces are designed to reduce the risk of pressure ulcer development by deforming in response to applied loads. They are designed to provide deep immersion and a high degree of envelopment of the individual to minimise sustained deformation caused by pressure concentrations over bony prominences. By contrast, active support surfaces, based on air, are recommended for individuals who are deemed to be at high risk of PUs. These surfaces are designed to reduce the risk of PU development by periodically transferring the areas of support between anatomical locations, so that deformation is not prolonged over any one tissue area. The weight-shifting feature is typically achieved by cycling air into and out of bladders that are located across the support surface, and are generally referred to as alternating pressure air mattresses (APAMs). There are generally equivalent supports surfaces in the form of cushions designed for use in sitting both in wheelchairs and leisure chairs. In addition, one common cushion used by many SCI individuals involves a matrix of balloon elements controlled at a static pressure and is universally known as the "ROHO" cushion. Pressure ulcers associated with spinal cord injury or cauda equina syndrome

Patients with SCI or CES present with distinctive features, which increase their relative risk of developing PUs. Typically, these individuals exhibit a significant lack of mobility, loss of sensation and an inability to reposition themselves. Relevant literature specific to PUs in SCI or CES individuals are discussed in subsequent sections.

1.4.5 Spinal cord injury – classification, functional consequences and rehabilitation pathway

An injury to the spinal cord has significant impact on both function and sensation. Both the severity and level of the spinal injury make a considerable difference to individual lifestyle.

Severity of SCI is allocated a score according to the ASIA classification chart as summarised in Table 1.2 (ASIA and ISCoS international Standards Commitee 2019). Muscle grade is defined in Table 1.3. Loss of function and sensation are also dependent on the level at which the spinal cord has been damaged, as detailed in Table 1.4.

Table 1.2: International Standards for Neurological Classification of Spinal Cord Injury (ASIA and ISCoS international Standards Commitee 2019)

A = Complete	No Sensory or Motor function is preserved in the sacral segments S4-S5
B = Incomplete	Sensory, but not motor function, is preserved below the neurological level and includes the sacral segments S4-S5
C = Incomplete	Motor function is preserved below the neurological level, and more than half of critical muscle groups below the neurological level have a muscle grade less than 3
D= Incomplete	Motor function is preserved below neurological level, and at least half of key muscles below the neurological level have a muscle grade of 3 or more
E= Normal	Motor and sensory function are normal

Table 1.3: Muscle grading definition (ASIA and ISCoS international Standards Commitee 2019)

Muscle Function Grading

0 = total paralysis

1 = palpable or visible contraction

2 = active movement, full range of motion (ROM) with gravity eliminated

3 = active movement, full ROM against gravity

4 = active movement, full ROM against gravity and moderate resistance in a muscle specific position

5 = (normal) active movement, full ROM against gravity and full resistance in a functional muscle position expected from an otherwise unimpaired person

5* = (normal) active movement, full ROM against gravity and sufficient resistance to be considered normal if identified inhibiting factors (i.e. pain, disuse) were not present

NT = not testable (i.e. due to immobilization, severe pain such that the patient cannot be graded, amputation of limb, or contracture of > 50% of the normal ROM)

Table 1.4: Levels of spinal cord injury (Hill Foundation for Families Living With Disabilities 2011)

Cervical Vertebrae Levels: C1 – C8	Cervical injuries above C4 level may require a ventilator for the individual to breathe. C6 injuries often enable shoulder and biceps control, but no control at the wrist or hand. C6 injuries generally yield wrist control, but no hand function. Individuals with C7 and T1 injuries can straighten their arms, but still may have problems with hand function.
Thoracic Vertebrae Levels: T1 – T12	The first thoracic vertebrae, T1, is located at approximately the same level as the top rib. Injuries in the thoracic region usually affect the chest and legs and result in paraplegia. For T1 to T8 injuries, there is generally control of the hands, but lack of abdominal muscle control. Lower T-injuries (T9 – T12) allow good trunk control and good abdominal muscle control.
Lumbar Vertebrae Levels: L1 – L5	Injuries to nerves in the area of L1 – L5 generally result in some loss of functioning of the hips and legs. Bowel, bladder and sexual function may also be impacted.
Sacrum Levels: S1 – S5	Injuries to S1 – S5 generally result in some loss of functioning in the hips, legs, ankles and feet. Loss of control of bowel, bladder and sexual functions is also common.

The rehabilitation pathway after SCI can differ according to the specific injury to the individual as well as the healthcare system which provides treatment. This thesis focuses on the rehabilitation pathway, which is specific to that undertaken by those who are treated by the NHS in the UK. Accordingly, a SCI individual will undergo a programme of acute and functional rehabilitation. Initial acute rehabilitation will take place either at a Major Trauma Centre (MTC) or District General Hospital (DGH). The location of acute rehabilitation is dependent on whether surgery or intensive care treatment is needed. In either case, if the spinal column is unstable, surgical fixation will take place during this period. If there is a delay before surgical fixation, there are a number of nursing techniques implemented to protect skin. Patients are periodically repositioned, using three to five nurses and possibly a collar to ensure the spinal column is maintained in correct alignment. In order to nurse a PWSCI on their side, pillows are placed underneath the individual to off-load tissue. It is essential to ensure the spinal column is kept in correct alignment whilst the patient is maintained on their side. A referral will then be made to one of the 12 regional Spinal Cord Injury Centres (SCICs) in the UK. The waiting time for a bed in a specialist centre can vary, from 1-6 months, dependent on whether respiratory support is needed. When a bed is available, a transfer will be made to the SCIC for functional rehabilitation. The time spent in functional rehabilitation can also vary, from 3 months up to a year for a ventilated patient (National Spinal Cord Injury Database 2020). After functional rehabilitation individuals will be discharged to their home, or a community interim placement, such as a nursing home. Interim placements are often utilised when rehabilitation goals have been reached, but the home still requires adaptations. It should be added that during the course of this thesis, with the emergence of the COVID 19 pandemic, there was considerable change to the normal rehabilitation protocols. The discharge process from the SCIC's was accelerated in order to facilitate faster admissions from acute hospitals. This was to allow for resources in the acute hospitals to be redirected to the Covid 19 pandemic.

1.4.6 Prevalence and incidence of pressure ulcers after spinal cord injury

In a prospective study performed in Switzerland, Scheel-Sailer et al. (2013) reported that 40.5 % of SCI patients referred to rehabilitation from September 2009 to February 2010 developed at least 1 Stage 2 -4 PU. In the US, Richard-Denis et al. (2016) retrospectively investigated a cohort of patients with SCI referred to functional rehabilitation for a 2 year period and revealed a PU prevalence of 33.6%. It is interesting to note that these authors also included stage 1 PUs. Garber et al. (2000) reported annual PU prevalence rates of 31% in the US community setting. A recent systematic review placed pressure ulcer prevalence in the SCI population at 32% (Shiferaw et al. 2020). It is accepted that reported prevalence rates will be variable, and are influenced by factors such as quality of clinical documentation and study methods. However, the proportion of patients referred to rehabilitation for SCI or CES who develop a PU is clearly significant. This ultimately reflects a negative experience for the individual.

1.4.7 Susceptibility and impact of pressure ulcers after spinal cord injury or cauda equina syndrome

Complete paralysis below the level of injury results in loss of muscle tone and inevitably tissue atrophy. This results in a higher proportion of adipose tissue with poor vascular response, making individuals vulnerable to pressure-induced damage (Bogie 2005). Indeed, it has been estimated that individuals with complete SCI presented with 32-43% less muscle volume and density relative to healthy controls. The corresponding values for individuals with an incomplete SCI was estimated at 14% (Moore et al. 2015). More recently, gluteal changes and abnormalities were imaged by Swaine et al. (2018) using ultrasound to investigate DTI in a small number of case studies. The findings supporting the importance of maintain muscle integrity was identified in a study in which skin tissue oxygenation was monitored in a SCI population. The authors revealed that tissue oxygen remained significantly lower under applied loading in sitting compared with basal levels in paraplegics with flaccid paralysis, but generally improved over a 12 month period for patients with all SCI individuals with spastic paralysis (Bogie et al. 1995). This categorisation was also found in a seminal monograph from researchers in Western Australia (Noble 1981), who reported that patients with flaccid paraplegia were most likely to develop PUs than those with spastic paraplegia.

It is well established that at a microvascular level, individuals with a SCI respond differently to applied loading than either able-bodied individuals or those presenting with orthopaedic trauma. As an example, research has revealed that the relative decrease in blood flow during uniaxial loading of sacral tissues in individuals with SCI was approximately two fold greater than individuals with orthopaedic trauma (Sae-Sia et al. 2007). However, this study did not distinguish between categories of SCI individuals, in particular, the levels of spinal injury. Other reports have confirmed that SCI results in a number of systemic disturbances, which can increase susceptibility to PUs. These include circulation, typically unstable blood pressure, sensory dysfunction, respiratory problems and digestion (Bogie 2005). Suggest that loss of neuronal control in chronic SCI, in conjunction with biomechanical risk factors at weight-bearing body sites, trigger a series of early-wound related processes in intact skin, mainly in the dermal – epidermal junction. This is essentially inferring SCI skin is ‘pre-activated’ for wound promotion. There is clearly a need to investigate the complex anatomical and physiological associations between PUs and SCI, with particular reference to potential associations with neurological level and severity of injury.

The development of a PU in an individual with SCI or CES has a negative effect on their rehabilitation and quality of life. Currently, it is advised and commonly practiced that these individuals should resort to “bedrest”, if they are suspected of developing a PU. However it should be noted, current guidelines do acknowledge bedrest can cause deterioration, and the decision to suggest bedrest should take into account both positive and negative outcomes (European Pressure Ulcer Advisory Panel et al. 2019). PUs can affect many different aspects of their life, including individual appearance, activity levels, employment prospects, health and relationships. A qualitative cross-sectional study assessed “self-esteem” in patients with paraplegia and reported that those who developed a PU had a significantly lower self-esteem than those not presenting with a PU (Blanes et al. 2014).

1.5 Summary

This chapter has described the structure of the skin and current definitions of PUs and DTI, in relation to an internationally recognised staging system. Established damage pathways leading to PUs have been discussed, which include mechanical loading leading to blood vessel occlusion, compromised lymphatic flow, ischemia-reperfusion injury and cell deformation. The evidence revealed continued high prevalence rates and significant impact of PUs, despite current interventional efforts to prevent these chronic wounds. In particular, it is evident that there is increased vulnerability to PUs after SCI or CES due to both extrinsic and intrinsic factors.

The aims and objectives of the proposed work will match a number of aspects of the current NHS priorities. As an example, establishing strategies to improve the prevention of PUs is an area for improvement in the NHS (NHS Improvement 2019). Given the high incidence, cost to service providers and patient impact of PUs there is a need to create novel strategies which prevent these chronic wounds from developing. As discussed in the previous chapter, PU development is multifactorial in nature and occurs in all patient groups. Indeed, individuals that acquire PUs can vary greatly in age, cognitive function and mobility. With the growing number of technologies available, it is increasingly possible to tailor new prevention strategies to the needs of a particular patient group. Therefore, the subsequent chapter will review the evidence relating to PU prevention strategies specifically after SCI or CES. Therefore, the subsequent chapter will review the evidence relating to PU prevention strategies specifically after SCI or CES.

Chapter 2 Literature review

Chapter 1 identified the clear clinical challenge of preventing pressure ulcers (PU) in individuals with spinal cord injury (SCI) or cauda equina syndrome (CES), and discussed the associated costs of treatment when PUs occur. In addition, the literature reveals the devastating impact of PUs on areas of life, including physical, psychological and social aspects (Section 1.4.2). Therefore, it is essential to identify innovative prevention methods, to ease the burden of PUs on both an Individual and at a wider societal level. Preventative strategies have been the focus for clinical innovation and research investigations to protect this vulnerable patient group. The following chapter will include a narrative review of the relevant scientific and grey literature on PU prevention for individuals with SCI or CES.

2.1 Search strategy

This review explored the following question:

What strategies and technologies are available to prevent PUs for individuals with SCI or CES?

The aims of the search and subsequent critique of the literature was to explore the evidence base behind clinically adopted PU prevention and investigate the current use of technology in preventing PUs for individuals with SCI or CES.

Specific studies involving fat grafting, early detection using inflammatory markers, ultrasound scanning and internal cooling were considered beyond the scope of this review. This is because the aforementioned prevention strategies involved surgical procedures or required specialised equipment that were not accessible to the researcher. As the goal of this literature review was to precede a prospective PU prevention study in a SCI rehabilitation setting, it was decided to include interventional studies involving an SCI cohort. Justification for inclusion/exclusion criteria is described in Table 2.1

The period over 1980-2021 was explored. CINHAL, MEDLINE, PSYCINFO and AMED databases were used for this search. The search criteria was as follows:

Table 2.1: Search terms and criteria for literature review

Search period		1980-2021	
Search terms		*Pressure Ulcer Prevention* *AND Spinal Cord Injury* *OR Cauda Equina Syndrome*	
Inclusion criteria	***Justification***	***Exclusion criteria***	***Justification***
1) At one intervention had to be included *2) At least 50% of the cohort presented with SCI.* *3) English Language* *4) Full text*	1) To support prospective study 2) To support further study in SCI rehabilitation setting 3) To be accessible to research team 4) To allow for thorough review of papers	*1) Fat grafting* *2) Early detection using inflammatory markers* *3) Ultrasound scanning* *4) Internal cooling*	*1) Beyond scope of study- Surgical procedure* *2) Beyond scope of study - Requires specialist equipment* *3) Beyond scope of study - Requires specialist equipment* *4) Beyond scope of study - Requires specialist equipment*

A total of 2509 results were identified using the search terms and databases. After title and abstract review, those studies that did not meet the inclusion/exclusion criteria shown in Table 1 were removed. Duplicates were removed. 65 studies remained. This process is outlined in Figure 2.1. The Critical Skills Appraisal Programme (2021) tool was utilized to support the critical appraisal of the literature.

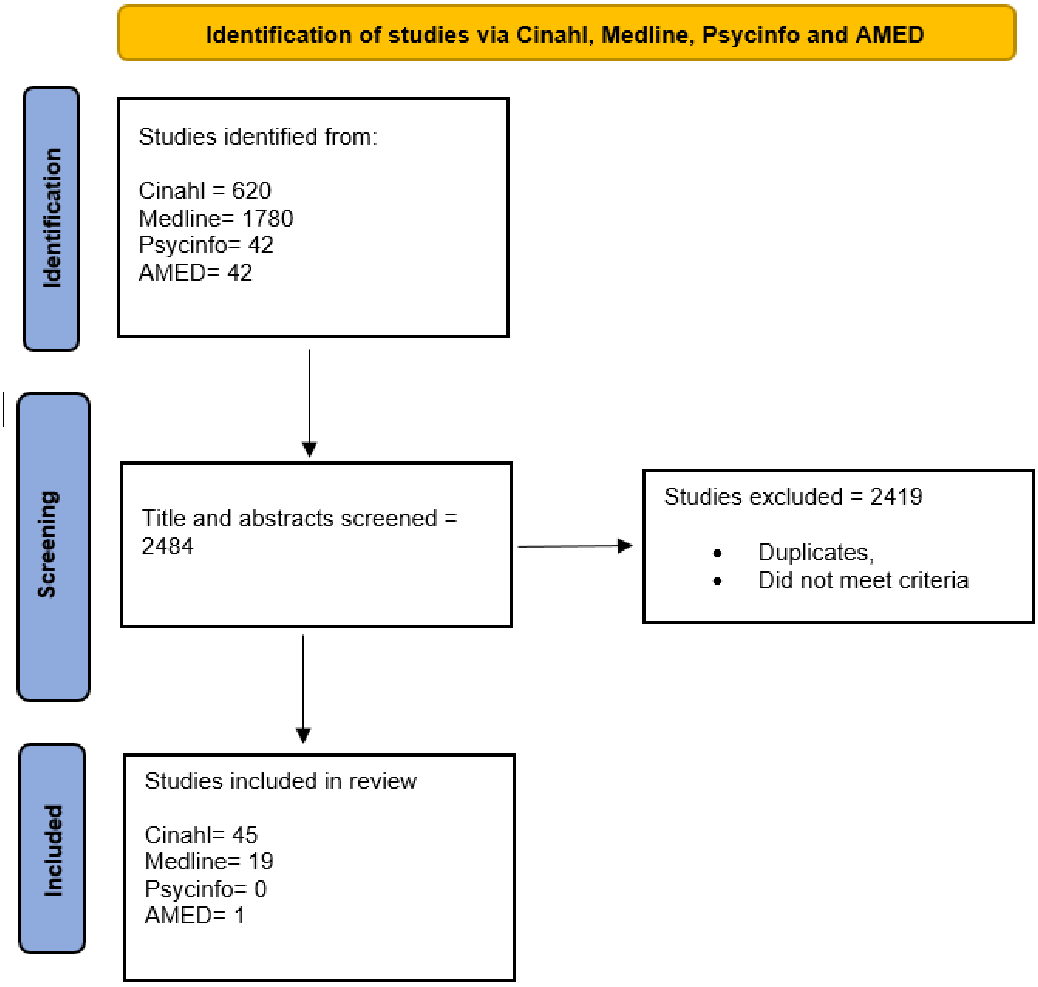


Figure 2.1: Literature search strategy presented in flow diagram, based on Prisma (2020)

Three broad themes emerged from the literature, namely, support surfaces and associated technology, repositioning, educational and behavioural intervention and these will be discussed separately to form the focus of the present chapter. Figure 2.2 demonstrates a literature map which shows the key themes and associated literature, based on an example by Creswell (2009).

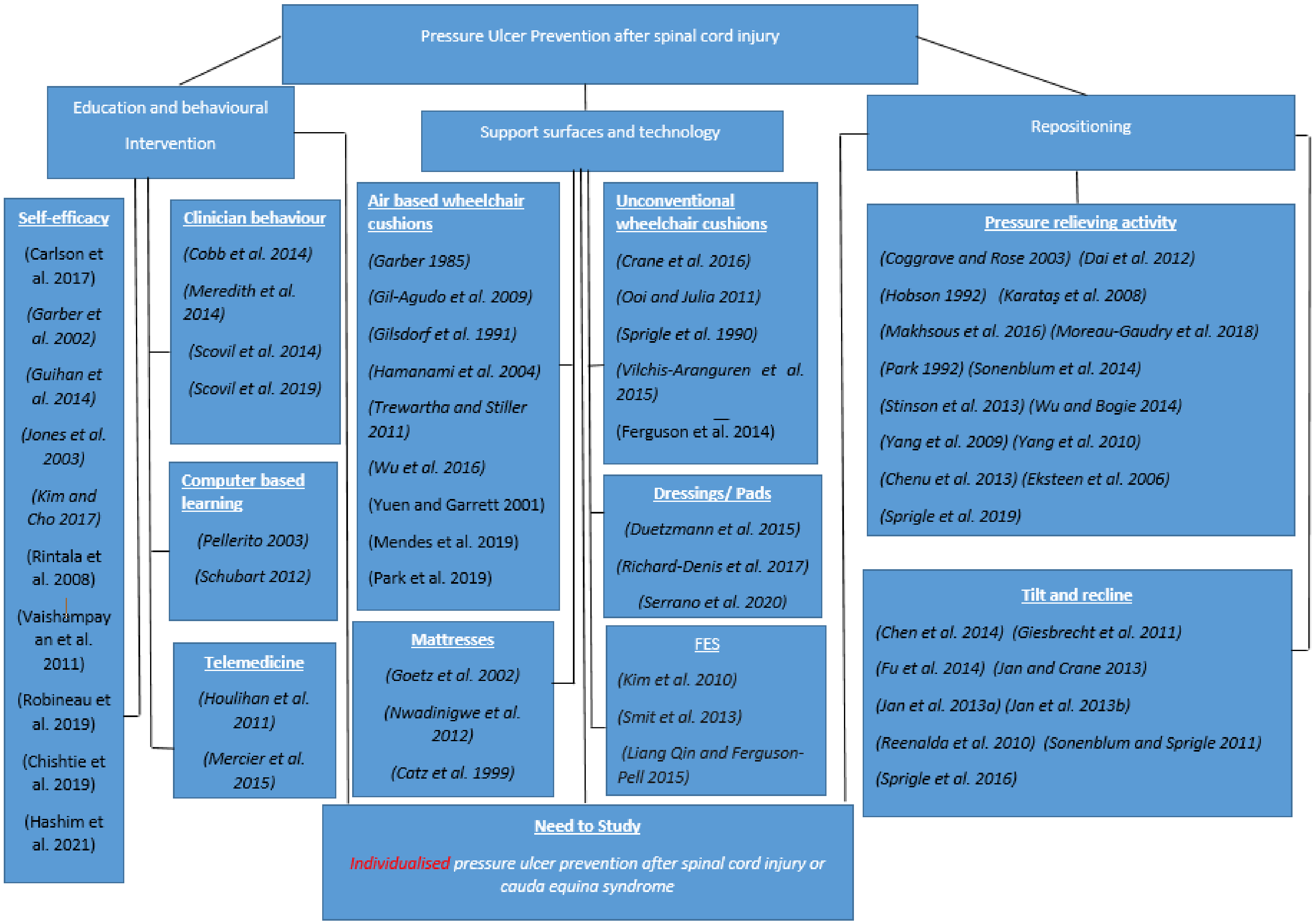


Figure 2.2 Litarature map depicting key themes and associated literature, based on an example by Creswell (2009)

2.2 Support surfaces and technology

Considerable research has focused on support surfaces as a means of PU prevention after SCI or CES. There is also an emerging body of work which has investigated the potential role of Functional Electrical Stimulation (FES) in PU prevention.

2.2.1 Air-based wheelchair cushions

Individuals with SCI or CES can spend on average 10 hours a day in a wheelchair (Sonenblum et al. 2016). Accordingly, the use of different cushion technologies has been assessed in studies involving persons with spinal cord injury (PWSCI). Most studies have generally involved small cohorts (<50), with only one study from 1985 involving >50 participants (Garber 1985). The outcome measure most frequently used was interface pressures, measured by a pressure sensing mat or pad (Garber 1985; Hamanami et al. 2004; Trewartha and Stiller 2011; Mendes et al. 2019; Park and Lee 2019). Other measuring devices include a force sensor plate to measure both pressures and shear forces (Gilsdorf et al. 1991), however this adapted sensor replaced the standard wheelchair seat, and thus these measurements did not accurately reflect the situation encountered by seated PWSCI. Two of these studies used patient satisfaction either as a primary outcome measure or a secondary outcome measure (Garber 1985; Wu et al. 2016). For example, the former authors analysed responses to specific questions such as wheelchair compatibility, ease of transfer, functional activities, and independence. By contrast, Wu et al. (2016) used a five point scale to assess satisfaction with dimensions, weight, adjustments, safety, durability, simplicity of use, subjective comfort and effectiveness.

Variability of response in interface pressures and, where appropriate shear, was a consistent theme across all the studies. For example Hamanami et al. (2004) investigated the optimal air pressure inside an air-filled cushion for individuals with SCI or CES. It was found that interface pressure could be reduced by manipulating the air pressure inside the cushion. However, there was no single internal pressure that guaranteed that all participants did not “bottom out” on the air cushion. Indeed, the authors postulated that the ideal pressure typically depended on the specific shape of the individual buttocks and the amount of soft tissue supporting the sitting position. In a small study of 10 participants, Mendes et al. (2019) reported that the ROHO air-based cushion was the most effective in producing the lowest peak pressure, whereas the Varilite air-based cushion performed best in terms of contact area supporting the thighs and buttocks. The largest study (Garber 1985), reported that the air cushion provided optimal interface pressures for only 50% of the 251 participants. In terms of participant satisfaction, many of the paraplegic participants reported that the presence of the air cushion made transferring/ moving in the chair more difficult. It is also important to note that studies involving interface pressure or shear force accounted for participants in the sitting position for relative brief “snapshots” of time up to 30 minutes or short distances of travel of 200 meters, due to the limitations of the technology. Thus they did not reflect the situation during normal daily activities in a wheelchair.

2.2.2. Unconventional wheelchair cushions

The use of “unconventional” and “contoured” cushions in pressure ulcer prevention after SCI or CES has also been examined by several authors in studies involving up to 11 participants (Sprigle et al. 1990). The outcome measure used in these studies typically involved interface pressures (Sprigle et al. 1990; Crane et al. 2016). However, in one study by Vilchis-Aranguren et al. (2015), several outcome measures were used including the Modified Ashworth Scale (MAS), Functional Independence Measure (FIM), skin reaction and a structured interview to assess user perspective. Indeed, the use of MAS is noteworthy as it indicates spasticity associated with each participant, which is rarely addressed when assessing wheelchair cushions. Interestingly, it was found that those with higher degrees of spasticity were less satisfied with the contoured cushion (Vilchis-Aranguren et al. 2015). A few studies, which assessed cushions which were constructed and contoured to match an individual morphology (Sprigle et al. 1990; Vilchis-Aranguren et al. 2015), reported a significant reduction in interface pressures. However, after two months of usage with the contoured cushions, Vilchis-Aranguren et al. (2015) reported that the these designs significantly affected independence in participants who presented with lower levels of injury and higher FIM scores. There were issues with perceived stability while supported on the cushion, which had a subsequent effect in confidence of performing functional activities independently. It is relevant that contoured cushions are designed for a single optimal posture, and are therefore less satisfactory to those individuals who need to reposition after transfers, perform independent activities or have high levels of spasticity. This finding again highlights the limitations of short-term mapping of interface pressure alone to fully assess the suitability of a particular cushion.

Although there was some correlation with reduced interface pressure, user satisfaction revealed variability in responses. This indicates that the decision on wheelchair cushion selection should be based on the individual and is multifactorial in nature depending on their care needs, mobility status and preferences. It is also inevitable that there is no “one particular” cushion that would be suitable for use with all individuals with SCI or CES (Regan et al. 2009).

2.2.3 Mattresses

There are comparatively few studies investigating mattresses used by individuals with SCI or CES. Nwadinigwe et al. (2012) explored the use of water mattresses as opposed to basic foam mattresses on a spinal ward in a trauma centre located in Nigeria, involving a cohort of 99 participants. The results revealed a significant decrease in the number of PUs acquired with the introduction of the water mattress. In particular, the incidence of PUs reduced from 60% to 25% in two years after the introduction of the water mattresses on to the ward. These findings, although representing PU as a primary outcome measure, do not lend themselves to generalisation to all SCI or CES populations, as they were conducted in an environment described by the authors as having “a weak infrastructure where patients generally pay out of pocket”. The foam mattresses originally used were also unbranded and not well described, which makes it difficult to compare with the castellated foam mattresses typically used in spinal centres in other parts of the world. It is also difficult to ascertain if the introduction of the water mattress was directly responsible for the decrease PU incidence, as a protocol with 4 hourly turns was introduced simultaneously as part of the study.

Goetz et al. (2002) compared 2 commercial alternating pressure air mattresses (APAMs) with 15 participants who presented with SCI or CES. The outcome measure, involving interface pressure measurements at the sacrum and ischial tuberosity over a period of 10 minutes, revealed no significant differences in the performance of the mattresses. As previously sated with wheelchair studies, this study only involved a “snapshot” of interface pressure values, due to the limitations of the pressure mapping technology. It also relevant that only minimum, maximum and mean interface pressures were recorded. Other relevant pressure-related parameters such as contact area and pressure gradient were not included. It is also problematic to measure interface pressures on a small area of the body when lying on a mattress, and not including areas such as the heels which are also at high risk of developing PUs in SCI or CES individuals (Brienza et al. 2017). In a separate feasibility study , reported involving 12 participants with SCI or CES, Catz et al. (1999)examined the effectiveness of a prototype mattress which continuously measured interface pressures, and adjusted air cells accordingly. Three inflations/deflations cycles of approximately 45 minutes would prompt pressure changes within the individual air cells, and adjust the individual pressure profiles. No participants were reported to present with pressure-related damage during this study, although participants complained of discomfort while supported on the mattress. A recent RCT which investigated the use of foam and alternating pressure mattresses in secondary/community inpatient facilities. No significant differences were found between high specification foam mattresses and alternating pressure mattresses. However, this RCT did not focus on PWSCI (Nixon et al. 2019b).

Interface monitoring technology has been significantly developed in the last decade, creating the means to assess patients for prolonged periods, while supported in both the chair and bed environments. Thus, for individuals with SCI or CES, there is an opportunity to employ monitoring technologies to assess both the performance of support surfaces and the corresponding movement patterns of individuals which may predispose them to pressure ulcers.

2.2.4 Dressing and pads

Dressings or prophylactic pads have also been assessed in PU prevention for the target sub-populations. As an example, one study involving 15 participants with SCI or CES investigated the use of a gel pad, placed underneath the sacral area, while lying on a foam mattress (Duetzmann et al. 2015). The outcome measures were interface pressures over 15 minutes and user satisfaction. A significant decrease was found in interface pressures in the sacral area. 70% of users with SCI or CES reported increased comfort rates with the gel pad. This study needed to be adapted to evaluate the extended use of the pads using pressure monitoring over a number of vulnerable body sites. This would enable assessment of the effects of the location of the pad on pressure distribution over the whole body in the lying position. . Indeed findings of patient comfort may also change if the pad were used long term. There is also a precautionary note on the use of prophylactic dressings that they do not preclude the regular assessment of the underlying skin.

A large prospective study involving 315 participants measured the effectiveness of a multi-layered foam sacral dressing versus a gel liner on a mattress during a period of spinal immobilization. The outcome measure was PU prevalence. The gel liner was used from 2010-2014, while the dressing was used from 2014-2016. This study found that PU were more prevalent with the use of the foam dressing, although the differences between periods were not statistically significant. The improved performance of the gel liner during the initial spinal immobilization phase, might be attributed to its ability to mould to the individual body shape. It is, however, difficult to isolate the effects of a single intervention when PU prevalence is the outcome, as many other factors and initiatives could have been introduced in the hospital environment during the study period, which may have impacted the findings. In addition, the conclusions are limited due to the non-random nature of the study protocol. . A recent study investigating the use of a foam sacral dressing applied after trauma, also yielded a non-statistically significant difference in terms of PU prevalence (Serrano et al. 2020). It is clear that the use of PU prevalence might seem the most appropriate primary outcome. However, reporting practices have been shown to be unreliable with many studies highlighting low levels of reporting and inconsistencies between healthcare professions, care facilities and policies between countries. These limitations are summarised in section 1.4.1

2.2.5 Functional Electrical Stimulation (FES)

FES studies have been performed to investigate its effects on numerous aspects of neuromuscular deficit following SCI or CES. This includes bladder control, upper limb function and both the prevention and healing of pressure ulcers. In terms of PU prevention, the effects of FES have employed various outcome measures including interface pressures, transcutaneous oxygen measurements, and the area and strength of gluteal muscles. These studies have observed some effects in reducing interface pressures by up to 38%, in addition to improving transcutaneous oxygen tensions and limiting muscle atrophy (Kim et al. 2010; Smit et al. 2013; Liang Qin and Ferguson-Pell 2015). For example, Kim et al. (2010) reported that the regular use of FES on the ischial tuberosities, temporarily increased transcutaneous gas tension (T_cP0_2) by up 78%. However, the effects might only be transient in nature and further work is needed to establish long term effects, particularly in terms of muscle atrophy and the optimal timing for intervention (Kim et al. 2010; Smit et al. 2016). Despite the promising findings, there are issues associated with the location of the electrode pads, which is critical for the stimulation effect. To address this, recent work has sought to develop FES stimulators into a wearable garment (Smit et al. 2013) . The effects of sacral root stimulators, which have previously been used to improve bladder function, has also resulted in a 29% reduction in on interface pressure over the ischial tuberosities (Liang Qin and Ferguson-Pell 2015). Liu et al. (2014) concluded that although positive effects on tissue health were noted, it is currently impossible to provide a definitive recommendations regarding the most adequate mode of FES, the optimal FES dose-response, training intensity, frequency, or duration. It is also important to note that the reductions in pressure values experienced with FES, do not represent the same magnitude of pressure relief, as possible with fully or partially off-loading of vulnerable tissues.

2.2.6. Summary

When analysing the literature describing the use of support surfaces and technologies for individuals SCI or CES, it is important to establish if the results are valid and if they could be extrapolated to a local population (Critical Skills Appraisal Programme 2021). This is problematic in the current body of literature. Many of the support surface evaluations are small-cohort studies or case-control studies, which have evaluated a wide variety of air, gel and foam support surfaces. The results from these small studies have not consistently identified an optimal type of support surface. In terms of technology, FES has shown promising results in terms of reduction of interface pressure, transcutaneous oxygen measurements, gluteal muscle area and strength. However, the long-term effects and the possible benefits of early FES intervention require further investigation.

Where larger RCTs have taken place there are serious methodological limitations. These include outdated pressure mapping technology or comparative arms taking place in different years, making it difficult to isolate the effects of a particular intervention. “A variable response” to intervention has often been reported. This could be attributed to the inherent variability among individuals with SCI or CES. In addition to variability in function caused by both level and severity of injury, this population also encompasses a wide range of ages, co-morbidities, socio-economic status and lifestyles. This suggests the benefits of adopting a highly individualized approach to PU prevention following SCI or CES involving support surfaces coupled with other interventions. It is also apparent that clinical study designs focused on a RCT format with PU prevalence as the outcome may not be the most appropriate within this SCI/CES population.

2.3 Educational and behavioural interventions

Studies have investigated the use of interventions that are designed to educate an individual with SCI or CES concerning PU prevention and subsequently influence healthy behaviour regarding this aspect of their care. This section critiques the use of education to improve clinical practice in relation to PU prevention in the target sub-populations.

2.3.1. Self-efficacy

The use of various educational and behavioural interventions to promote self-efficacy has been the subject of a number of RCTs. However, it is evident that when newly developed PU incidence is used as an outcome, many of these trials have failed to reach statistical or even clinical significance. As an example, Carlson et al. (2017) and Guihan et al. (2014) used modular educational content as an intervention and newly developed PU incidence as an outcome measure. The order and content of the education could be adapted to a certain extent based on the individual. Neither of these trials resulted in a decrease in PU prevalence and with both reporting a loss to follow up in the recruited participants. As previously discussed, using PU prevalence as an outcome measure can prove problematic, as it is very difficult to isolate the effects of particular interventions when PU development is inevitably multifactorial in nature. It also involves prohibitive sample sizes to demonstrate an effect, and it is relevant that both Guihan et al. (2014) and Carlson et al. (2017) recognise that their studies were underpowered.

Similar modular educational content to promote PU prevention has been used in other studies (Garber et al. (2002); Kim and Cho (2017); Robineau et al. (2019), Chishtie et al. (2019); Hashim et al. (2021) However, they each used knowledge of PU prevention or skin care beliefs as an outcome measure. The intervention groups of these studies did show significantly improved knowledge when compared to the control groups. It would have been beneficial to examine whether any targeted behavioural changes might have occurred as a result of this improved knowledge. This could be achieved via monitoring technologies, as discussed in Section 1.2.6.

In contrast to the pre-determined modular content, Jones et al. (2003) and Rintala et al. (2008) adopted a more individualized approach. The former authors explored the use of monetary contingencies and regular practice nurse visits to increase self-efficacy and prevent PUs in a small study involving 9 participants. The Pressure Ulcer Scale for Healing (PUSH) score was used as the outcome measure. PUSH scores are visual assessments of skin. It should be noted, this can be subjective and opinions can vary between healthcare professionals. PUSH scores were significantly lowered, indicating healthier skin, after the implementation of regular scheduled visits with the practice nurse and regular payments. By contrast, Rintala et al. (2008) investigated the use of highly individualized 1:1 education sessions for individuals with SCI or CES during a hospital stay for surgical repair of a PU followed by monthly follow up post discharge. PU recurrence and time to recurrence were used as outcome measures. The intervention group of this trial was associated with a reduced PU recurrence rate and were significantly slower to develop a PU where recurrence did occur. It is apparent that these two studies demonstrated both an individualized and flexible approach to improve self-efficiency and this might have contributed to their significant findings.

2.3.2 Clinician behaviour

There are also studies which investigated the use of education and behavioural intervention to improve clinical practice. These studies use implementation science, and communication tools, such as daily “huddles” to improve skin care. (Cobb et al. 2014; Meredith et al. 2014; Scovil et al. 2014; Scovil et al. 2019a). The measures typically involve documentation-based outcomes, for example involving Braden scores, and prescription for pressure relieving support surfaces. These studies all reported significantly increased compliance to PU-related documentation and the use of pressure relieving equipment. Although investigations into clinician behaviour are useful indicators of clinical standards and routines, it is limited in terms of how this translates into effective PU prevention for individual patients. Indeed it would be useful to utilize biofeedback and long term pressure monitoring technologies to evaluate how these improvements affect outcomes for patients. This has been used with good effects in other settings, such as Intensive Care Units (ICUs) or older persons in the community (Behrendt et al. 2014; Aylward-Wotten 2017).

2.3.3. Computer-based learning

Two small studies examined the use of computer-based learning as the primary intervention (Pellerito 2003; Schubart 2012), involving completion of an e-learning module by SCI participants. Pellerito (2003) involved three participants and used the observation of pressure reliving activity as the outcome measure. This activity significantly improved following the computer-based intervention. However, the authors recognised that the observational periods were relatively short (<24h), and specify future work should seek to observe pressure relieving activity over extended periods. Schubart (2012) studied 14 participants and used a pre / post intervention questionnaire as an outcome measure. Again, knowledge of PU prevention significantly improved after the computer learning was undertaken. However, there are obvious limitations to these studies, in that direct short-term observation carried out by a researcher could have influenced the actions of the participant. The questionnaire also demonstrates a temporary retention of knowledge, as opposed to a longer-term change in behaviour.

2.3.4 Telehealth

Two studies have investigated the use of an automated telehealth system called "Carecall" (Houlihan et al. 2011; Mercier et al. 2015). After a successful pilot study, 106 participants with SCI or CES were divided into intervention and control groups. This system delivered a series of educational scripts designed to support self-care and management. A series of tools were used as outcome measures, including PUSH and self-reported depression severity. The "Care-call" system significantly reduced depression scores for patients after 6 months of the system being implemented. However, no statistically significant differences in PUSH scores were reported. This suggests face-to-face contact with a clinician could be important in terms of effective PU prevention.

2.3.5 Summary

In summary, educational and behavioural interventions have been shown to have a positive impact on PU prevention, with a number of small studies showing improvements in PU knowledge and prevention of recurrence. These interventions proved most effective when they were individualized and targeted at a specific behaviour. Face to face contact with a clinician may also prove an important factor when considering PU prevention, with a large telehealth trial failing to show significant results in terms of skin integrity and health. This may be due to the visual nature of skin inspection. When assessing a wound, a number of features are assessed, including size, colour, depth, smell and temperature. This can be problematic if the wound assessment is being conducted remotely. These studies have also shown it is problematic to use newly developed PUs as an outcome measure, with no studies showing significant results in this area.

In terms of larger RCTs, there is a "variability" in outcome, which also emerged when discussing the literature surrounding support surfaces. When large numbers of the SCI or CES population are involved, they are often grouped independent of their spinal level or severity of injury. This creates heterogeneity in the groups, despite the fact that there are direct established associations with PU risk according to the nature of the injury (Brienza et al. 2017). Again, this body of literature suggests highly individualized PU prevention strategies are needed.

2.4 Repositioning

2.4.1 Tilt and recline

The use of tilt and recline in a wheelchair has been investigated in a number of small cohort studies, which have typically involved interface pressures and transcutaneous oxygen measurements as outcome measures. These studies have revealed significant correlations in these parameters with respect to the effectiveness of tilt and recline strategies. For example, tilt angles of 25-30 degrees combined with recline angles of 100-120 degrees significantly decreased pressure and increased blood flow when compared to values associated with upright sitting (REF). Indeed a decrease in interface pressures with a corresponding increase in blood flow were correlated with the angle of tilt of recline (Giesbrecht et al. 2011; Sonenblum and Sprigle 2011; Jan et al. 2013a; Chen et al. 2014; Sprigle et al. 2016). Additionally, the duration of time needed in the tilt recline position to significantly recover tissue perfusion and decrease pressure was reported to be 3 minutes (Jan et al. 2013b).Indeed , these findings concur with a previous study investigating the recovery of tissue perfusion after loading and subsequent pressure relieving activity (Coggrave and Rose 2003). Although these studies do show tilt and recline to be effective in changing the biomechanical and physiological factors associated with PU risk, these angles can be somewhat difficult to achieve and maintain in everyday life, particular with the functional demands of for PWSCI or CES. Fu et al. (2014) produced a preliminary report on a model, which utilizes machine-learning to provide personalized guidance on the usage of tilt and recline in the seated position. The model benefitted from consideration of the individuality and variability associated with the SCI or CES population. However, it is still difficult to match such an activity with aspects of activities of daily living, for example eating, conversation and work. Nevertheless, when considering that individuals with evidence of skin marking are often placed on periods “bedrest”, a personalized tilt and recline regimen may provide an effective alternative care strategy. This would need to be evaluated on a case-by- case basis, as the correct equipment and settings, concordance and thorough monitoring would be required.

2.4.2 Pressure relieving activity

The use of pressure relieving activity has also been assessed in studies. Using interface pressure and transcutaneous oxygen parameters, it has been widely established that movements, such as forward and side leaning, can be effective in off-loading pressures and restoring tissue perfusion (Hobson 1992; Park 1992; Stinson et al. 2013; Sonenblum et al. 2014). However, the efficacy of the traditional “push up” has been questioned in the literature. For example, studies report that traditional “push up” manoeuvre needs to be performed for an average of 1 minute 42 seconds to be effective (Coggrave and Rose 2003; Wu and Bogie 2014; Makhsous et al. 2016), a period often prohibited in those SCI or CES individuals with diminished upper limb strength and core control. Although these studies in the UK and US involve relatively small cohort numbers, their results are generally consistent and suggest that a return to off-loaded tissue perfusion is difficult to achieve using a traditional “push up” manoeuvre.

Karataş et al. (2008) examined the Centre of Pressure (COP) displacement in participants with SCI or CES when compared with healthy volunteers to assess the magnitude of movement in the sitting position and its corresponding ability to allow tissues to recover. Participants were asked to perform maximum unsupported forward, backward, right and left trunk leans. It was found that COP displacement was smaller in participants with SCI or CES than in healthy volunteers. Within the former group, participants with a history of PUs were also found to have smaller COP displacement than those with no history of PUs. These findings strongly suggest that inadequate magnitudes of movement designed to relieve vulnerable tissue sites could prove a factor in PU development. Interestingly, it was found that those with low thoracic injuries showed less COP displacement in backward leans, than those with high thoracic injuries. The authors note this could be due to several reasons, including a reduced reliability in the analysis of backward lean, or the development of postural muscle usage over time. These considerations warrants further investigation. Additionally, the impact of ASIA score on displacement of COP was not investigated in this study.

Resistive sensors and pressure mats have been used to investigate the *frequency* of pressure relieving activities. Yang et al. (2009) used a series of resistive sensors to investigate how often twenty individuals with SCI or CES performed pressure-relieving movements. The participants spent a mean time of 9.2 (range 3.2 – 12.2) hours a day in the wheelchair with mean continuous periods of 97 (range 24-284) minutes without performing a pressure relieving activity. When audio feedback was introduced to prompt participants, the frequency of these pressure-relieving movements did increase, from a mean of 9.48 times per day to 12.30 times per day. However, these values were still lower that the levels recommended for performing a pressure relieving activity, namely, every 15-30 minutes (Yang et al. 2010). The author cites Garber (2001) and Kirshblum (2005) for this recommendation. An interesting case study was carried out by Chenu et al. (2013) monitoring one paraplegic individual in the community for six months. A sensing mat was created using layers of piezo-resistive sensors, with data being collected by a small central unit equipped with a flash card. Video monitors were placed in the participant's home, to correlate activities with those recorded by the pressure monitor. This showed interesting results in terms of general trends seen in everyday activity. The findings were similar to those described by Yang et al. (2010) with pressure relieving movements being performed infrequently. For example, forward leans per day MEAN= 2.05.

Moreau-Gaudry et al. (2018) analysed pressure-reliving activity on a pressure map over a 1 hour recorded monitoring session. The pressure map allowed for monitoring of frequency and magnitude of pressure relieving activity, which were reported to improve after the introduction of a tongue display unit (TDU). However, it was found that TDU unit was not convenient for use in everyday life. The participant did find the pressure mat could be practically and comfortably used in everyday life. This suggests this technology involving pressure mapping could be feasibly used to monitor wheelchair activity for longer periods of time. Indeed, there is a need to extend monitoring beyond an hour to capture a true reflection of posture and mobility during the day and night-time periods. This has been used successfully in other subject groups who have decreased mobility, such as older persons in the community (Aylward-Wotten 2017). Recently these authors have investigated pressure relieving activity for 17 participants during longer periods of sitting of up to 7 days. The authors report that the daily in-seat behaviour of people varies widely and no consistent trends were found over time, or across the cohort. There was no investigation of correlations of in-seat behaviour in terms of level of injury or ASIA. The authors did establish that PWSCI often overestimate the number of pressure relieving movements they are performing. This shows the need for reliable recording of pressure relieving activity over a 24 hour period.

2.4.3 Summary

There is limited evidence involving large cohort studies to evaluate the efficacy of pressure relieving activities or tilt and recline. However, there are a substantial number of small cohort studies with similar findings, which show the effectiveness of these strategies in decreasing pressures and increasing blood flow over the ischial tuberosity and sacral areas. However, it is notable that these studies have only monitored participants for short periods of time largely in a research setting. The feasibility and efficacy of these strategies when integrated in an individual's everyday life has yet to be fully explored. Long term pressure monitoring technologies could be utilized further to assist in integrating these activities into everyday life. This would also allow for the monitoring of the frequency and magnitude of such activities. Indeed this approach has been successfully adopted in the community with older persons with decreased mobility (Aylward-Wotten 2017).

2.5 Discussion

There is a wide body of literature focused on PU prevention for individuals with SCI or CES, which involves both in-patient and out-patient settings. . This can be broadly categorized into three areas involving support surfaces and technology, education and behavioural interventions, and repositioning.

In both RCTs and a number of small studies where support surfaces have been investigated, particularly involving wheelchair cushions, a variable response has often been reported, with little statistical significance in reported PU prevalence. It is important to acknowledge the heterogeneity in the SCI or CES population when describing these findings. Factors to consider include age, time since injury, co-morbidities, lifestyle in addition to functional ability. Therefore, it could be suggested that the prescription of support surfaces should represent a highly individualized choice. The outcome measurement most frequently used at present is interface pressures, assessed over short periods of time, typically up to 1 hour. This does not provide adequate information about the long-term performance of a support surface and would clearly benefit from the advantages offered by long term pressure monitoring technologies and biofeedback. This approach could be used in conjunction with factors such as comfort, stability, and the ability to perform pressure relieving activities. There is currently a dearth of literature available on the performance of mattresses as used by individuals with SCI or CES in the lying position. Where they have been evaluated it has not involved, a full body sensor array. Indeed, considering sacrum, heels and ischial tuberosities represent frequent areas of pressure damage following SCI or CES, it is important to assess the performance of support surfaces used throughout the day and night, involving both mattress and cushion systems as patient transfer between devices.

Educational and behavioural intervention can be effective in PU prevention after SCI or CES, with encouraging results reported in PU knowledge, healing and recurrence. These interventions appear to work best when individually targeted at a specific behaviour and should involve face to face contact with a clinician. There are a number of RCTs available in this field although, as with support surfaces, a variability in response is often evident. This suggests that individualized PU prevention strategies are necessary. Indeed, biofeedback and long-term pressure monitoring have been used to assist behavioural intervention in other settings, such as older persons care. It would advantageous to utilize these approaches with the SCI or CES sub-populations. Indeed, the utilization of appropriate technology represents a key aim of the NHS long term plan, outlining a commitment to develop new technologies to meet the evolving needs of patients in the future decade (NHS 2019)

Finally, there are a number of small studies which confirm that repositioning via a pressure relieving activity or wheelchair tilt and recline manoeuvre is effective in decreasing interface pressure and increasing blood flow to pre-loaded values , assessed with both pressure mapping and transcutaneous oxygen. However, there are difficulties in integrating these activities into the everyday life of an individual. Many of the previous studies have taken place within a research setting, with measurements recorded over a relatively short time period. Where resistive sensors have monitored for longer periods of time, the range of movements have been performed infrequently. It is important to ensure that these activities are effective in both frequency and magnitude of movements during the everyday activities of the individual.

Technologies that can both monitor and promote movement, assisting those living with PWSCI are critical to our future digitally enabled care provision. PWSCI present with a lack of sensation and mobility, but have an increasing life expectancy. Indeed, both clinicians and patients would benefit from an integrated, automated mobility analysis for unobtrusive and repeatable assessment that will enable the tracking of mobility over time.

2.6 Conclusion

PU development is multifactorial in nature and by implication research to evaluate interventions to support their prevention is complex and difficult to achieve. This review has shown that appropriate support surfaces, technology, for example pressure mapping, behavioural and education interventions, in addition to effective repositioning strategies can reduce specific risk factors associated with PUs. However, the challenge lies in addressing the inherent variability among the target population, which has previously been discussed. To address this problem, it is critical that intervention is tailored around the individual, in addition to being provided with effective monitoring and support. An individualised plan, with regular biofeedback and contact with a clinician, could be used to support individuals with SCI or CES to adopt effective PU prevention strategies into their everyday routines. Thus, there is a need to utilize developments in monitoring technologies to assess an individual PU prevention activity, including support surfaces and repositioning, then subsequently create an individualized PU prevention plan. This will form the basis of the main study whose aims objectives are detailed in chapter 4.

Chapter 3 A retrospective evaluation of pressure ulcer prevalence after spinal cord injury.

To identify specific phase of the rehabilitation which could be addressed in a prospective study, retrospective data on pressure ulcers (PUs) was collected from the inpatient and community population of the Duke of Cornwall Spinal Treatment Centre over a period of 18 months. This Spinal Treatment Centre represents a tertiary healthcare provider, which accepts referrals from both primary and secondary healthcare, providing lifetime follow-up to the individual following their hospital admission. The spinal cord injury (SCI) inpatient rehabilitation journey is divided into 4 different "phases", as briefly outlined in Table 3.1.

Table 3.1: Phases of inpatient rehabilitation at the Duke of Cornwall Spinal Treatment Centre

Phase	*Mobilisation status*
1	Pre- mobilisation – the *patient is primarily care for in the bed, with short periods in armchairs and transfers for rehabilitation*
2	Mobilised to a wheelchair– *the patient is provided with a wheelchair and specialist cushioning support to facilitate their rehabilitation and independence. They sit out in their chair for short, supervised periods.*
3	Up 4 hours a day – *the patient is encouraged to spend longer periods in their wheelchair (up to 4 hours), where they are more independent with managing their pressure care whilst sitting.*
4	The 2 weeks running to discharge and on discharge– *patients are prepared for living in the community and plans are made to facilitate their transition and meet their care needs.*

As well as providing inpatient rehabilitation and outpatient appointments, the Spinal Treatment Centre also employs 2 Community Liaison Nurses (CLN). When a patient under the care of the Spinal Treatment Centre is living in the community and develops a PU, they are managed by their local district nurses in the first instance. However, if the PU is not healing or may even need surgery, the district nurses will contact the CLN for assistance. The corresponding details of the patient and their pressure ulcer are then documented by the CLN, with records maintained at the Spinal Treatment Centre.

The retrospective PU data from the CLN reports were assessed to identify the number of pressure ulcers in both the acute (inpatient) and community settings. Key factors implicated in the pressure ulcers were assessed including patient factors of rehabilitation phase, level of injury, ASIA score, age and sex. Specifically the following aims and objectives were identified:

3.1 Aims and objectives

3.1.1 Aims

- Interrogate retrospective data relating to PU prevalance in patients with SCI over a 18 month period.
- Use this retrospective data to inform the design of a prospective study which investigates the role of personalised care and technologies for preventing PUs.

3.1.2 Objectives

- Determine the severity and location at which PUs most frequently developed in the inpatient phase of rehabiliation
- Determine which of the factors associated with demographics, rehabilitation and injury level predispose patients with SCI or cauda equina syndrome (CES) to the development of PUs

3.2 Methods

This study represents a retrospective evaluation from a distinct patient cohort derived from the 18-month period from 1st August 2015 to 28th February 2017. A number of inclusion and exclusion criteria were considered when analysing the retrospective data set.

3.2.1 Inclusion criteria

- In-patients admitted to the spinal centre with a SCI

- Patient with a SCI seen in the community from Aug 2015-Feb 2017
- Patients presenting with a stage 2, 3 or 4 pressure ulcer, diagnosed by healthcare professionals working on the SCI unit.

3.2.2 Exclusion criteria

- Under 18 years
- In-patients in the spinal unit who did not present with a SCI (were admitted to the centre due to the lack of beds in other areas of the hospital).
- Patients presenting with a stage 1 PU. This data was not routinely reported on the central as DATIX system.

3.2.3 In-patient data

The following steps were taken to obtain the in-patient data.

Step 1) In-patient data was derived from the computerised hospital adverse event reporting system DATIX. This lists the patients admitted to the Spinal Treatment Centre, under a spinal speciality, that were reported to have stage 2-4 PUs during their stay. This includes those presenting with PUs that were acquired in a referring hospital.

Step 2) After identifying patients from this list, their medical and nursing notes were requested, to extract further information. These include level of injury, ASIA score, stage of PU, location of PU and phase of rehabilitation.

Set 3) In order to estimate prevalence of PUs, the total number of admissions to the Spinal Treatment Centre for initial rehabilitation during the study period was obtained. This information was accessed through the National Spinal Cord Injury Database (National Spinal Cord Injury Database 2020), with the proviso that this database was only accessible by registered clinicians via NHS network computers. This data was thus accessed through the clinical role of the researcher. All data was anonymised as source and ethical permission for the study was granted prior to data extraction and analysis (ERGO 25797).

3.2.4 Community Liaison data

The following steps were taken to obtain out-patient data.

Step 1) Community data was regularly updated on an excel spreadsheet, maintained by the CLN's, detailing all the visits to individuals with PU's. In particular, this identified the stage and location of the PU. Community data was derived from this spreadsheet.

Step 2) CLN notes were requested to extract further information relevant to the study. All data was anonymised as source and the same ethical permission covered this analysis.

3.2.5 Statistics

Descriptive statistics and frequencies were used to analyse the retrospective data. The number of individuals presenting with a pressure ulcer divided by the total number of SCI patients over the 30-month period was used to establish the prevalence over the study period.

3.3 Results

153 patients were admitted to the Duke of Cornwall Spinal Treatment Centre for initial rehabilitation during the 18 month period. The demographics of each patient, including as, age, level and severity of injury are described below.

3.3.1 Pressure ulcer statistics from inpatients in the Spinal Cord Injury Treatment Centre

In total, 29 stage 2-4 PUs were reported on the DATIX system. These PUs were acquired by 25 patients, representing a 16% prevalence rate of all patients admitted for initial rehabilitation during the assessment period. In terms of the incidence rate, 7% of patients admitted developed a new PU while undergoing rehabilitation at the Spinal Centre.

Figure 3.1 indicates the phase in which patients initially developed a PU. It can be clearly observed that there are two primary rehabilitation phases in which PUs occur, represented by pre-admission and phase 3 of rehabilitation. It should be noted that the phases of rehabilitation are constructs with variable time lengths. How long persons with spinal cord injury (PWSCI) remain within each phase varied from person to person. This must be considered when interpreting the results. For example, phase 3 can often be extended due to the fact that it involves most of the functional rehabilitation activities. This prolonged duration could have potentially resulted in the higher number of pressure ulcers being observed during this phase of rehabilitation. The data available did not allow for corrected prevalence rates according to the time in each phase

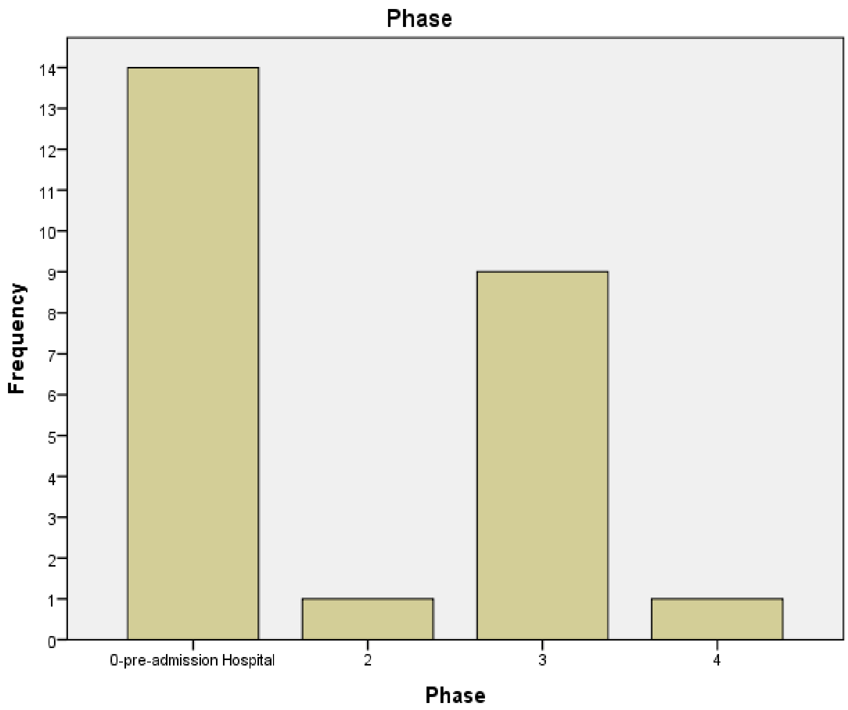


Figure 3.1: Phase of rehabilitation in which patients initially developed a pressure ulcer.

In terms of outpatients, the cohort involved patients who developed severe and chronic PUs. They were subsequently referred to the Spinal Treatment Centre when the local community services required advice. 65 patients were referred to the community liaison service. These patients had acquired a total of 74 PUs. Each visit conducted by community liaison had been allocated a main clinical need, which was recorded. Visits to manage individuals who predominately needed advice for PUs encompassed 28% of the total community liaison activity during this period.

3.3.2 Location of pressure ulcer

The locations in which PUs most frequently developed in the inpatient cohort were analysed according to the DATIX input. PUs most frequently developed on the sacrum (48%) or feet/heels (37%), as indicated in Figure 3.2. With respect to the 74 PUs acquired in the 64 outpatients, the distribution of the locations are illustrated in Figure 3.3. In this case, the PUs occurred preferentially at the buttocks (40%), hips (27%) and sacrum (18 %).

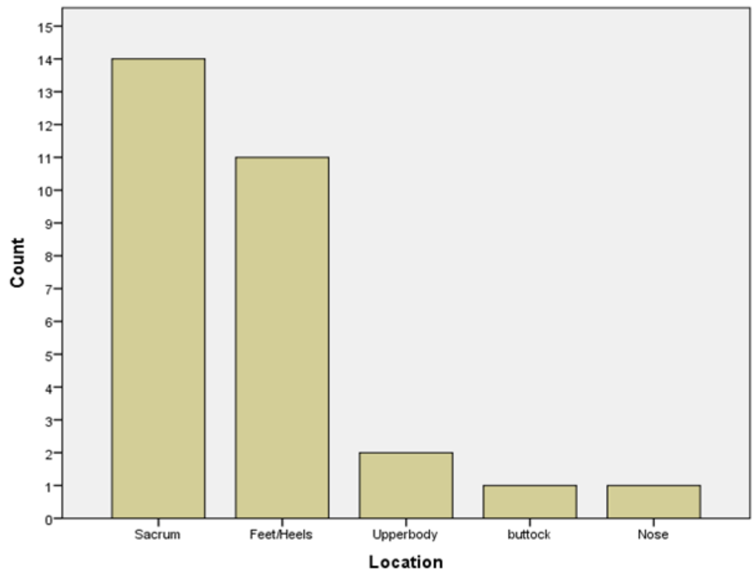


Figure 3.2: Location of pressure ulcer (n=29) acquired in the inpatient cohort

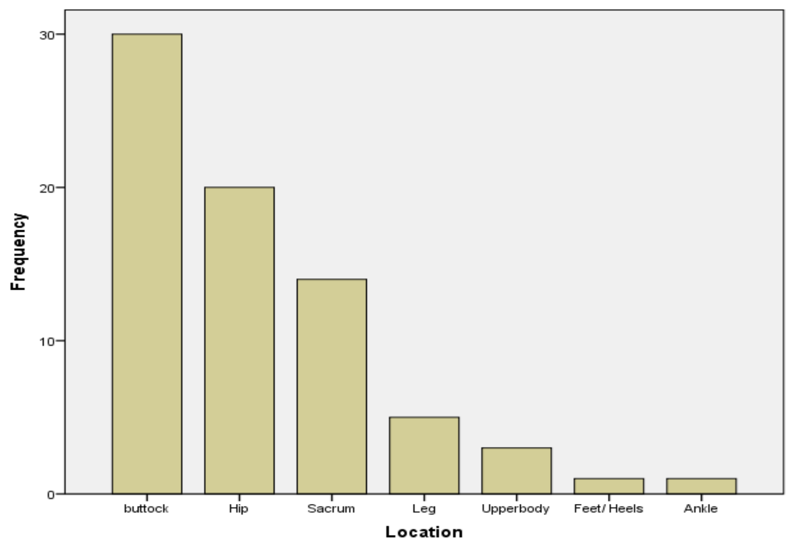


Figure 3.3: Location of pressure ulcer (n=74) acquired in the outpatient cohort

3.3.3 Stage of pressure ulcer

Of the 29 PUs acquired by 25 inpatients, Stage 2 PUs represented the most frequent acquired (62%), as illustrated in Figure 3.4. By contrast in out-patient cohort, the most frequently presented to the community liaison service were stage 4 PUs (37%), as illustrated in Figure 3.5. This clearly reflects the contrasting wounds which are referred to the outpatient service (typically severe wounds needing specialist support).

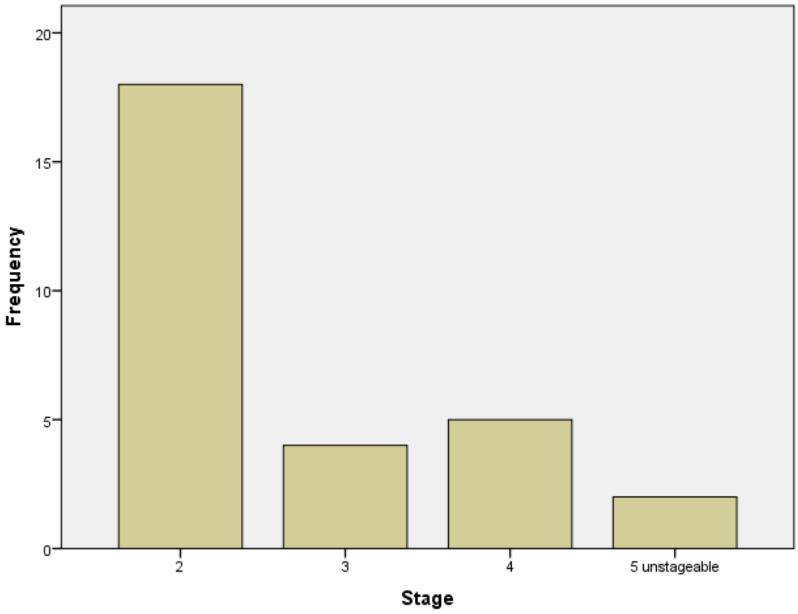


Figure 3.4: Stage of pressure ulcers (n=29) acquired in the in-patient cohort

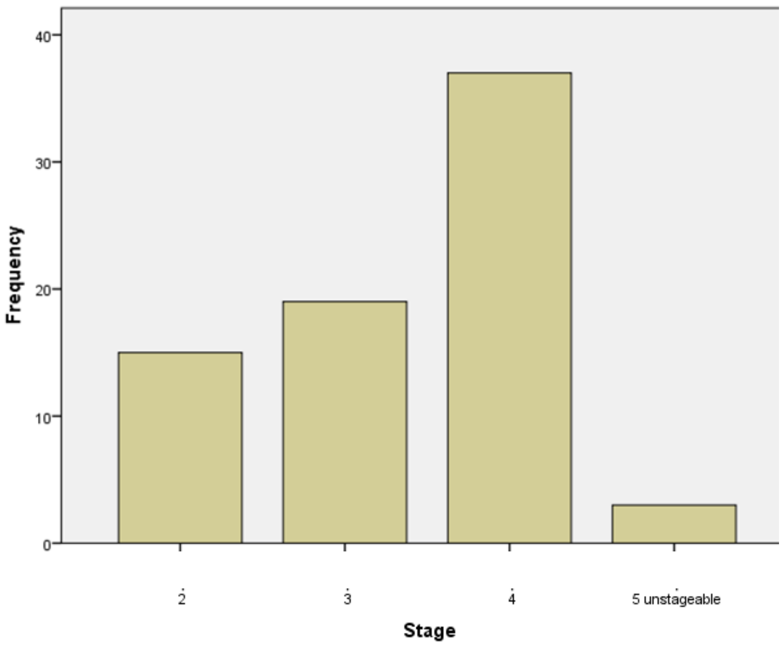


Figure 3.5: Stage of pressure ulcers (n=74) acquired in the out-patient cohort

3.3.4 Severity of injury

In the in-patient cohort, SCI individuals who most frequently acquired a PU, were those with an ASIA score of A (36%), as illustrated in Figure 3.6. Nonetheless, individuals with score B-D also presented with PUs. A similar trend was evident with the out-patient cohort, as illustrated in Figure 3.7. The most severely injured individuals were the most likely to acquire a PU, with a high percentage (80%) attributed to an ASIA score of A.

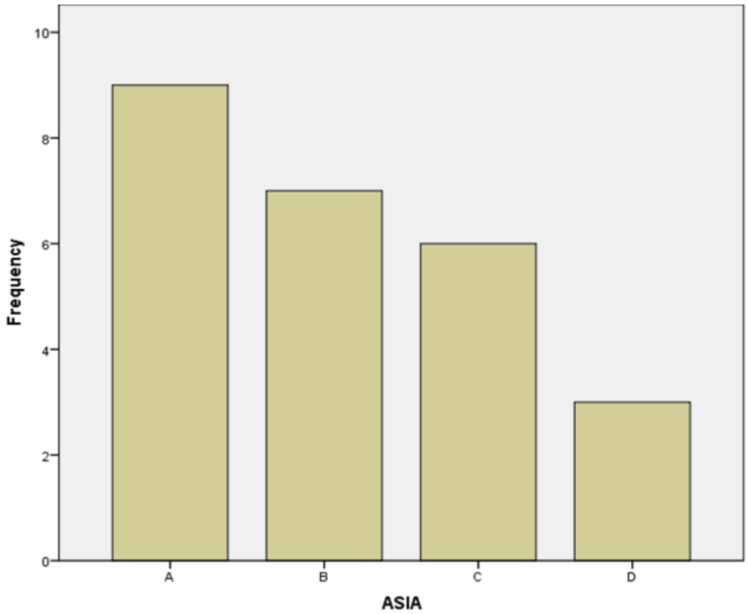


Figure 3.6: ASIA demographics of in-patient cohort who acquired a pressure ulcer

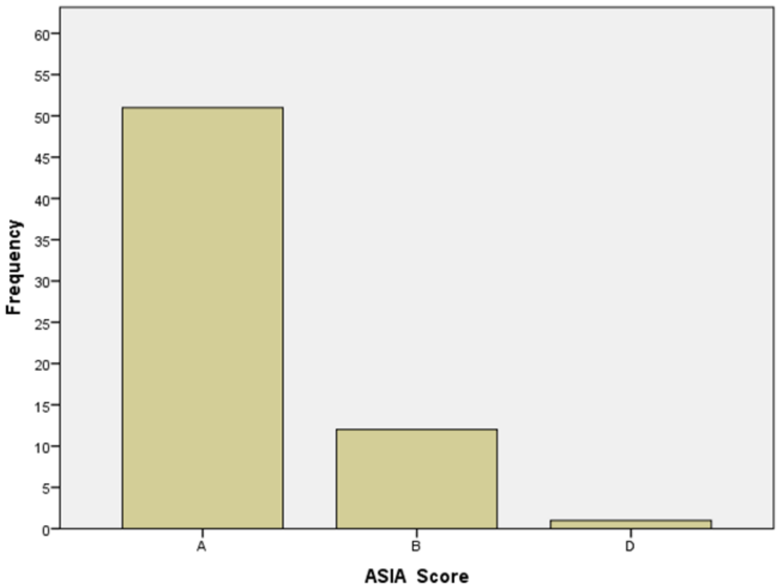


Figure 3.7: ASIA demographics of outpatient cohort who acquired a pressure ulcer

3.3.5 Level of injury

The “spinal level of injury” relates to the level of the spinal cord at which power and sensation have been altered. Injuries below the level of T12 are referred to as CES. As illustrated in Figure 3.8, the highest proportion of PUs were found in in-patients (N=153), who presented with a neurological deficit at C5 (16%) and C6 (16%). Indeed 52% of the in-patient cohort presenting with PUs had injury levels in the cervical region (C4-C7), while 46 % had injury levels in the thoracic region (T4-T12). Only 1 individual (4% of total) presented with an injury in the lumbar region (L1)

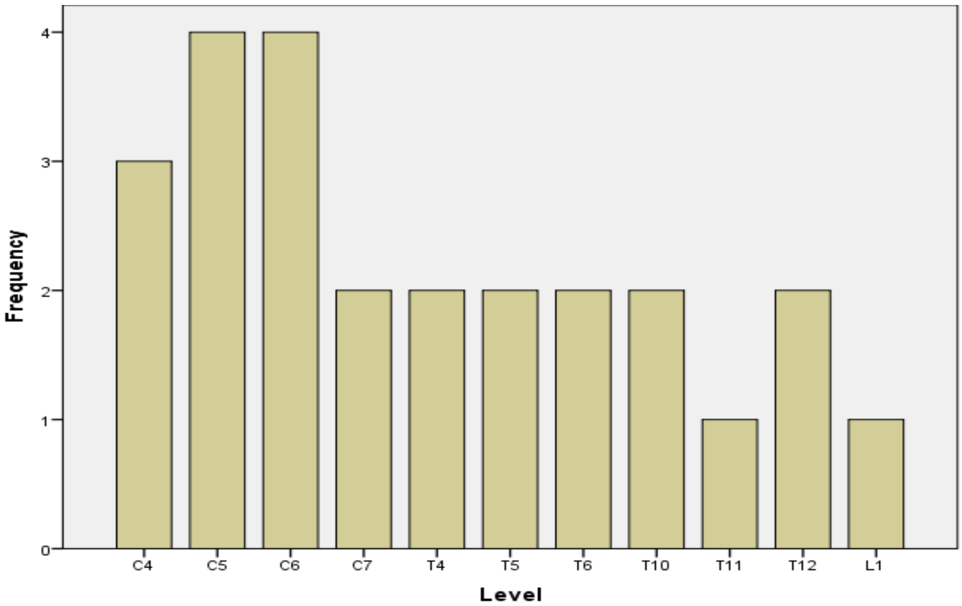


Figure 3.8: Spinal level of injury of in-patient cohort who acquired a pressure ulcer

The corresponding data for out-patients is presented in Figure 3.9. The highest proportion of PUs were presented in individuals with injury levels C6 (9%) and C5 (8%). 45% of the outpatient cohort studied were injured in the cervical region, 50% in the thoracic region (T2-T12). In this cohort, 3 patients (5%) of the total presented with an injury in the lumbar region (L1). It is possible that the larger proportions of C5 and C6 represented in the cohort of patients who acquired a PU could be due to a larger number of injuries in these regions This warrants further investigation. The level of injury for all admitted PWSCI to the spinal cord injury centre (SCIC) was not available for the retrospective analysis conducted in the present study.

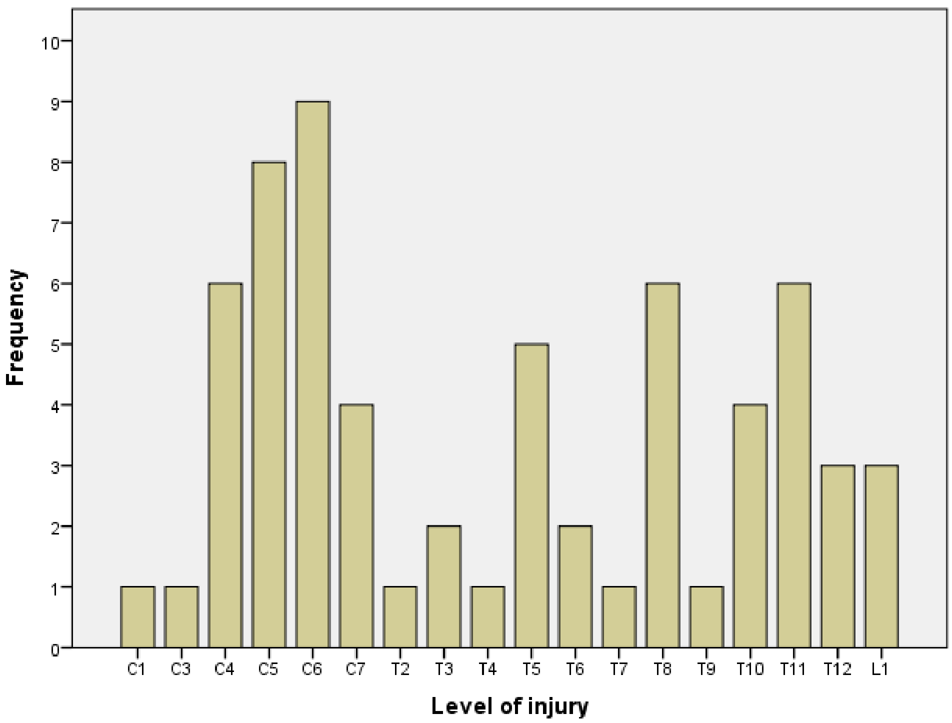


Figure 3.9: Spinal level of injury of out-patient cohort who acquired a pressure ulcer

3.3.6 Age

Individuals aged 18-30 (36%) most frequently acquired stage 2-4 PUs in the in-patient cohort, as demonstrated in Figure 3.10. By contrast, in the out-patient cohort, in individuals in the age range of 41-50 years (21%) were the most frequent to acquire a PUs, as illustrated in Figure 3.11. There were evident differences between the distribution of the frequencies between inpatient and outpatient data sets, with the former being bimodal in nature and the latter being a more traditional bell shaped curve.

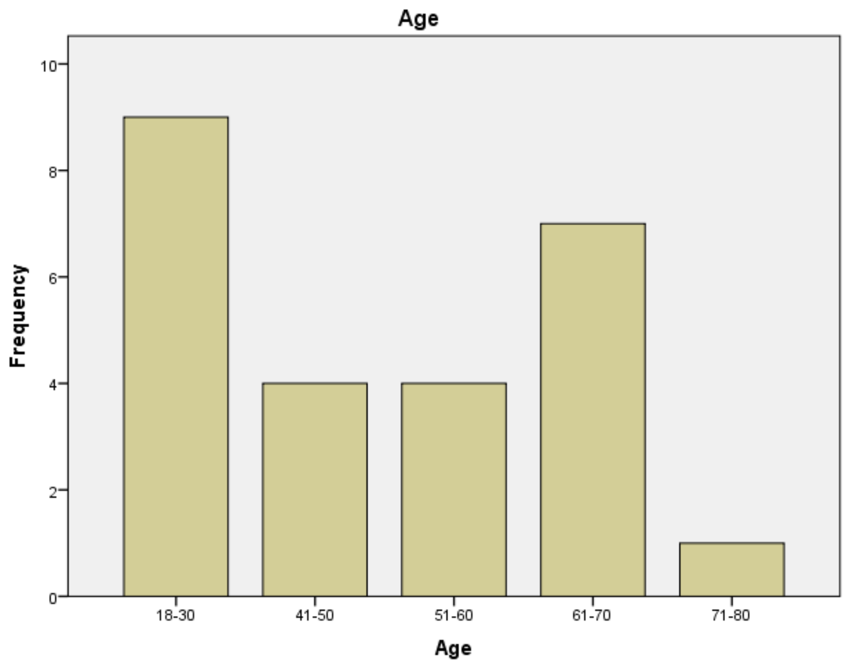


Figure 3.10: Age distribution of in-patient cohort who acquired a pressure ulcer

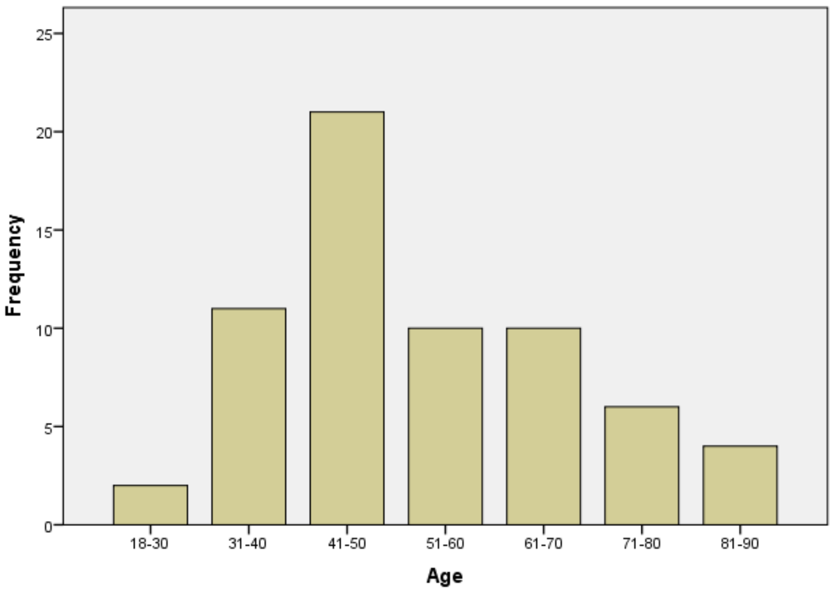


Figure 3.11: Age distribution of out-patient cohort who acquired a pressure ulcer

3.3.7 Years post injury

PU occurrence in SCI out-patients was also collated into the time post injury as illustrated in Figure 3.12. It is evident that individuals acquired PUs over a considerable range of time post injury. However, individuals were most frequently referred to the spinal centre with a severe PU 6-10 years after their initial injury, representing 25% of total cases in the out-patient cohort.

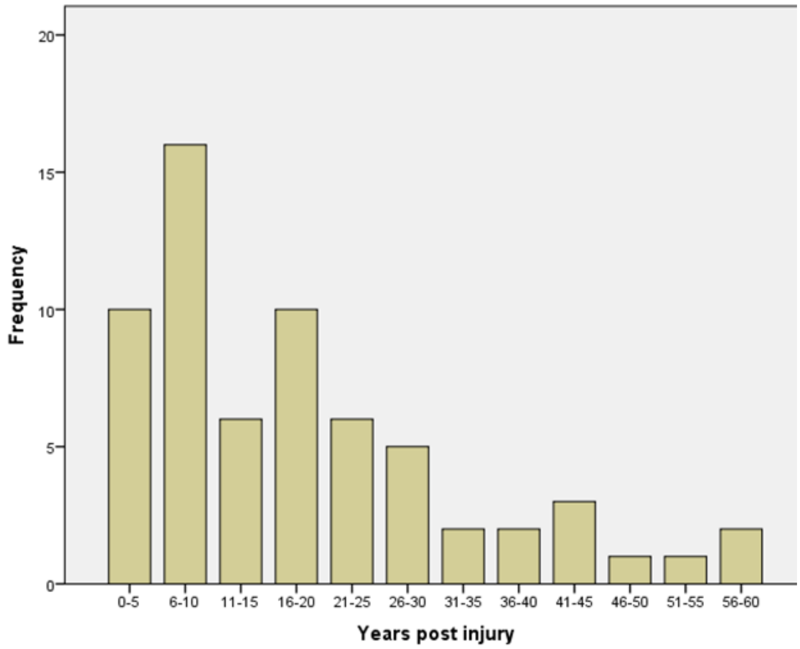


Figure 3.12: Distribution of years post injury of out-patient cohort who acquired a pressure ulcer

3.4 Discussion

In the present study, 16% of patients admitted for initial rehabilitation to the Spinal Treatment Centre acquired a stage 2-4 (or un-stageable) PU. This could have occurred pre-admission during acute care, or during rehabilitation at the Spinal Treatment Centre. This represents a lower value than that reported in recent PU prevalence studies investigating in-patient care following SCI or CES. For example, Brienza et al. (2017) in the US observed a prevalence rate of 37.5 %, while Richard-Denis et al. (2016) reported that 33.5 % of patients acquired a PU *before* admission to a rehabilitation centre in Canada . In addition, Scheel-Sailer et al. (2013) reported that 40% of patients admitted for acute and functional rehabilitation in Switzerland acquired stage 2-4 PUs. All of these studies were based in a specialist rehabilitation centre or referring hospitals and incorporated similar-sized cohorts. However, both the former two studies included stage 1 PUs, which were not used in the present retrospective study. Indeed, stage 1 PUs represent the most common PUs in patient cohorts. It should also be acknowledged, there are key some differences in methodology, which are potential causes for the lower prevalence rate found in the present study. As an example, both Brienza et al. (2017) and Scheel-Sailer et al. (2013) represent prospective studies. By contrast, retrospective data is highly reliant on the accurate reporting from clinical staff and indeed underreporting is common which will inevitably impact on the number of PUs included in the dataset.

Despite the relative lower prevalence rate, namely 16%, this value still translates into a significant cost to both healthcare provider and patients. For example, the development of a PU during the lengthy in-patient stay will inevitably delay discharge home. Indeed Scheel-Sailer et al. (2013) estimated that the average length of stay in patients who had a PU was 5 times longer those who did not present with a PU. The latter will include a period of "bedrest" for the patient to relieve pressure specifically over sites at which skin damage is present. These events are costly in terms of both the extra bed-days spent in hospital and the wellbeing of the patient, and it results in a delay in the progress of the rehabilitation phase.

The present study confirms earlier prevalence studies, which revealed an association between PU development and ASIA score (Scheel-Sailer et al. 2013; Richard-Denis et al. 2016). The data revealed that 36% of patients who developed a PU had an ASIA score of A (or complete lesion), with lower values as the trend in injury severity lessens (Figure 3.6) . Indeed, one prospective study reported that patients with an ASIA score of A were 4.5 times more likely to acquire a PU than those with an ASIA score of B, the latter being classified as a patient who has retained a degree of sensation (Brienza et al. (2017). This trend is also apparent with the out-patient data, with 80% of this cohort with PUs presenting with a Grade A ASIA score (Figure 3.7). Thus, both in-patient and out-patient SCI cohorts suggest the level of sensation is important in determining PU risk (Table 3.2).

It might be assumed as individuals who acquire higher level of injury would be more vulnerable to PUs than those with lower levels of injury, who have more function and ability to transfer body weight. However, the present findings corresponds to previous data which failed to indicate a significant relationship between level of injury and PU prevalence (Ash 2002; Scheel-Sailer et al. 2013; Richard-Denis et al. 2016). Indeed, a seminal monograph analysing data from a SCI centre in from Australia suggested a greater degree of PU development in paraplegic patients when compared with quadriplegic (high spinal level) patients (Noble 1981). This was explained by examining tissue oxygen levels under applied load which tended to improve during initial rehabilitation for quadriplegic patients while deteriorating for those with paraplegia (Bogie et al. 2005). Indeed, these authors suggested that this is because the spasticity experienced by individuals with high levels of lesion results in reduced loss of muscle bulk, when compared to individual paraplegics with flaccid paralysis. Independence and activity levels are also higher in those with paraplegia, which could lead to the neglect of skin health-related behaviour. In terms of age, a large proportion of the in-patient cohort investigated in the present study were 18-30 (36%), illustrated in Figure 3.10. This differs to the outpatient cohort, where the largest proportion of individuals referred to the spinal centre for PU management were 41-50 (32%), as shown in Figure 3.11. It could be suggested lifestyle and personality of the individual are critical in determining this, although this is inevitably an area which warrants further investigation. As an example, case-studies would be an effective way to explore potential links between age and PU development. In addition, many of the inpatients were of a younger age. By contrast, outpatients who have established SCI covered a wider age range and thus this could have affected the distribution of PU data.

The location of PU reveals significant differences in the in-patient and outpatient cohorts of this study (Figures 3.2 and 3.3). In the former, the most frequent location of a PU is the sacrum (48%) followed by the feet/heels (37%). By contrast, PUs in the outpatient population occur at the buttock (40%) and hip (27%). There are wide range of causes to PUs, which are inevitability multifactorial in nature. It is feasible that sacral PUs are related to lying postures, particularly during prolonged periods on the back or sat-up in bed during rehabilitation, which concentrates high pressure on the sacral tissues. Indeed, Sae-Sia et al. (2007) reported that unloaded and loaded sacral temperatures were higher in individuals post SCI, than those with other types of trauma and healthy volunteers. It could be suggested that hospital mattress covers and disposable bed protection pads may have a detrimental effect on the microclimate, contributing to the large percentage of sacral PUs. However, this hypothesis is largely based on clinical experience and observation and requires further investigation. The high incidence of PUs located at the buttock and hip in the outpatient cohort, could be attributed to prolonged sitting postures and increased temporal atrophy over the gluteal muscles, particularly during phase 3 of rehabilitation (Table 3.1).

The retrospective evaluation also revealed that there is an apparent peak at 6-10 years post injury (25%) in outpatient data where individual present with severe PUs, as revealed in Figure 3.12. It is essential to integrate protective skin-health behaviour into an individual care programme, which can be practically continued for many years in their post-discharge environment and lifestyle. As discussed in Chapter 2, lifestyle choices play a significant role in pressure ulcer prevention adherence. It could be hypothesised that following discharge there is a decline in adherent behaviour as other social influences play a role in individuals choosing or forgetting to perform pressure ulcer prevention activities e.g. off-loading, seated leaning or periods out of the wheelchair.

The in-patient cohort results show the reported proportion of stage 2 PUs (62%) was similar to the corresponding values in relevant studies i.e. 34% - 64% (Scheel-Sailer et al. 2013; Richard-Denis et al. 2016; Brienza et al. 2017). The PUs investigated in the out-patient cohort of this retrospective study frequently developed to a greater severity (Figure 3.5). This might be predicted, as this cohort has been referred to the Spinal Treatment Centre due to the severe and chronic nature of these PUs. It also significant that Scheel-Sailer et al. (2013) found the most severe PUs observed in their analysis, had developed in distinct community settings in Switzerland.

One aspect of PU development investigated in this retrospective study, which has not been accounted for in previous studies, involves the phase of rehabilitation, using a UK spinal centre model, in which patients initially develop a PU. In other countries , Scheel-Sailer et al. (2013) and Richard-Denis et al. (2016) reported that patients were more likely to acquire a PU during the initial acute rehabilitation phase in a referring hospital, as opposed to during functional rehabilitation at a specialist centre. The results found in this retrospective study also reflect this, with 56% of patients initially developing a PU in a referring hospital prior to admission the spinal centre. The interesting feature of the present findings, however, is that 36% of patients in the in-patient cohort initially developed a PU during phase 3 of rehabilitation, as opposed to only 4% in phases 2 or 4 (Figure 3.1). This indicates the enhanced risk of developing a PU increases when individuals begin to mobilise in a wheelchair for more than 4 hours a day. During this phase, it is probable that patients become increasingly independent and self-reliant on managing their own skin-health demands, and thus have to establish habits which are conductive to this.

It is important to note, episodes of moisture associated skin damage (MASD) would not have been reported on the DATIX system. These episodes can be frequent following SCI or CES and usually result in periods of bed rest. In that respect, the full extent of skin-related health issues experienced by patients after SCI or CES is not reflected in the present data. Since this study was performed, it been decided by Salisbury NHS Foundation Trust that all episodes of MASD are to be reported on the DATIX system.

3.5 Conclusion

The retrospective evaluation of inpatient and outpatient PU data revealed a prevalence of 16% in the spinal cord Injury unit. It is also relevant the outpatient cohort showed a large number of severe and chronic stage 4 PUs. Key demographic factors included ASIA score, with Grade A having the highest frequencies of PUs. In addition, those with C5/C6 level injuries were most frequently observed to develop PUs in both the inpatient and outpatient cohorts of this study. Although a similar proportion of individuals who acquired PUs had a cervical or thoracic level of injury. An original finding of this study involves the phase of functional rehabilitation in which individuals most frequently acquired a PU. Previous studies have shown that individuals are more likely to develop a PU during acute rehabilitation whilst in a referring hospital, prior to being admitted for functional rehabilitation in a specialist centre. This study has shown that individuals are likely to develop a PU both in the pre-admission phase to a specialist unit and during phase 3 of their functional rehabilitation. The latter represents the time in which mobilising in a wheelchair for more than four hours a day is promoted. It is therefore evident that intervention which is targeted at an individual's PU prevention strategies during the transition to wheelchair mobilisation is required and thus represents the focus of the following PhD thesis.

Chapter 4 Material and methods

The goal of this research was to perform a longitudinal evaluation of pressure relieving movements in sitting and lying postures in a cohort of spinal cord injured individuals. A commercial pressure monitoring system was used to provide spatial pressure data which would act as a surrogate for movement. The resulting pressure data was used to support patient feedback and deliver an IPPUP. A cohort of individuals with spinal cord injury (SCI) who had been referred to the Duke of Cornwall Spinal treatment Centre were recruited to the ethically approved study (December 2018- Jan 2019). A longitudinal approach to data collection was adopted to capture both inpatient and community data. Quantitative information describing the frequency, magnitude and duration of movements were recorded using the pressure monitoring technology, in addition to evaluations of distinct postures adopted on a range of support surfaces. Complementary information describing barrier and facilitators to pressure ulcer (PU) prevention was collated using a series of interviews in time-points 1 and 2. Individualised pressure ulcer plans were prescribed based on the combined pressure monitoring and interview information, created in time-point 1 and further refined in time point 2. Pressure monitoring was also performed in the community following discharge (timepoint 3), where patients were based in a variety of care and home settings. Time-points 1, 2 and 3, are outlined below

Timepoint 1; baseline assessment of posture and mobility during rehabilitation in the hospital setting using the continuous pressure monitor

Timepoint 2; follow up assessment of posture and mobility following the implementation of the IPUPP intervention to promote pressure ulcer prevention.

Timepoint 3; final monitoring assessment in the community following discharge to different care settings (home, residential care and nursing homes).

Example individualized pressure ulcer prevention plans (IPUPP) are shown in Appendix 1. The following research questions have been proposed, answered in the subsequent chapters (Chapters 5-7).

4.1 Research questions

1. Can sensing technologies involving long term monitoring be used repeatedly to evaluate posture and mobility in a cohort of spinal cord injured during different stages of rehabilitation?
2. What are the intrinsic factors associated with the magnitude and frequency of movements in persons with spinal cord injury (PWSCI)?
3. Can the use of monitoring technology inform a pressure ulcer prevention plan designed to increase the quality and frequency of pressure relieving activities?
4. How do the extrinsic factors associated with discharge into the community affect the frequency and type of postural movements performed in the bed and chair environments?

4.2 Aims and objectives

Global Aim

To evaluate the use of continuous pressure monitoring for the assessment of posture and mobility in a cohort of patients with spinal cord injury

Aim 1. Assess factors affecting posture and mobility in PWSCI

Objectives

a. To recruit a cohort of PWSCI during phase III or IIII of their inpatient's rehabilitation.
b. To collect data on their demographics, injury level and skin status
c. To implement the continuous pressure monitoring technology in the bed and chair for a minimum 24 hours.
d. To analyse the pressure monitoring data and use it as a surrogate for movement.
e. Collect information on PWSCI perception of current PU prevention methods via short interview

Aim 2. Determine whether adoption of a personalised pressure ulcer prevention plan (IPUPP) influenced the posture and mobility behaviour in PWSCI during their inpatient rehabilitation.

Objectives

f. To perform repeat assessments of PWSCI during their inpatient stay to evaluate changes in posture and mobility post IPUPP.

g. Interview PWSCI patients to elicit patient perspectives on the IPUPP

Aim 3. Assess factors affecting posture and mobility in PWSCI following discharge to the community

Objectives

h. To follow up PWSCI in the community setting and perform continuous pressure monitoring evaluations in their home or care settings.

i. Compare the frequency and nature of movements performed in community setting to those estimated in the inpatient SCI rehabilitation unit.

4.3 Methods

To achieve the aims of the study a longitudinal observational approach was used, on a heterogeneous sample of SCI inpatients. A quantitative repeated measures approach was utilized to provide data on parameters of mobility and interface pressure during both lying and sitting. Evaluations were conducted both in a specialist rehabilitation unit (inpatient) and following discharge to the community. Interviews were conducted with patients to understand factors affecting their ability to follow PU prevention advice. An IPUPP was subsequently created in the inpatient setting, to promote posture and mobility strategies to prevent pressure ulcers.

The study was led and implemented by a clinical academic nurse, with recruitment supported by the nursing leads of the spinal cord injury wards (two primary wards for recruitment). The research lead conducted skin checks and assessed all pressure relieving activities according to the continuous pressure monitoring data. The researcher liaised with clinical colleagues to ensure support surfaces were properly maintained. To understand the lifestyle changes associated with skin health that occur following SCI the study also included interviews.

4.4 Sample and setting

To achieve the aims it was important to focus on a sub-group of individuals with SCI, who were present the Duke of Cornwall Spinal Centre during the study period. The sub-group of individuals who were recruited, were undergoing rehabilitation and had been judged to be capable of “sitting out” in their wheelchair for at least four hours per day. This represented phase 3 of their rehabilitation, a critical phase of high pressure ulcer risk, as identified in Chapter 3.

4.4.1 Inclusion criteria:

- Current inpatient in Duke of Cornwall Spinal Treatment Centre.
- SCI or cauda equina syndrome (CES).
- Regularly sat in wheelchair for more than four hours per day (phase 3 of rehabilitation).

4.4.2 Exclusion criteria:

- Inpatient at the Duke of Cornwall Spinal Treatment Centre who did not present with a SCI or CES, who were admitted to the centre due to the lack of beds in other areas of the hospital.
- Unable to speak and/or understand English
- Under 18 years of age

In addition to these inclusion and exclusion criteria, the Duke of Cornwall Spinal Treatment Centre has its own policy on admission. This includes the following exclusions for the unit.

4.4.3 Exclusion criteria for admission to Duke of Cornwall Spinal Treatment Centre:

- Progressive diseases of the central nervous system, including malignant disease involving the spinal cord
- Cerebrovascular events
- Injuries to the brain, but not including the spinal cord
- Spina Bifida
- Cerebral Palsy
- Patients with major mental health disorders, which may interfere with physical treatment/rehabilitation, or those sectioned under the MHA
- Severe brain injury with a significant cognitive deficit or behavioural problems

- Patients with co-morbidities which may affect their ability to undertake spinal rehabilitation (For example cognitive dysfunction)

When analysing data from Duke of Cornwall Spinal Treatment Centre, from the period August 2015-Feburary 2017, PUs occurred most frequently either pre-admission to the specialist centre i.e. while in a referring hospital or during phase 3 of rehabilitation (Figure 3.1). In addition, this phase of the rehabilitation facilitates promotion of situational awareness and self-management that can be continued when the individual is transferred to the community.

As previously highlighted there is considerable variation among the SCI population cohorts, with respect to physiology, demographics and lifestyle. For this study it is important to yield results that provide high quality detailed descriptions of each case, in addition to shared patterns that are common across cases. For example, it is optimal to investigate each participant across three time points, however it is also important to investigate the impact of the intervention on those with different levels and severity of spinal injury. This allows for the observation of commonalities and differences within the SCI population. Therefore, maximum variation sampling was employed. 6 participants with injury levels T6 and above were recruited, in addition to 6 participants with injury level T6 and below.

4.4.4 The recruitment process of patients

Regular meetings occurred in the Spinal Treatment Centre between each patient and the Discharge Co-ordinator as part of the standard in-patient care. Patients in rehabilitation phase 3 were identified by the Discharge Co-ordinator and given the participant information sheet. The patients were then given sufficient time to consider the information sheet, which stressed that future care would not be affected if the patient chose not to participate in the study at any time. After 48 hours, the SCI. Nurse Specialist/ Clinical Doctoral Research Fellow the patient. The entire recruitment process is outlined in Figure 4.1.

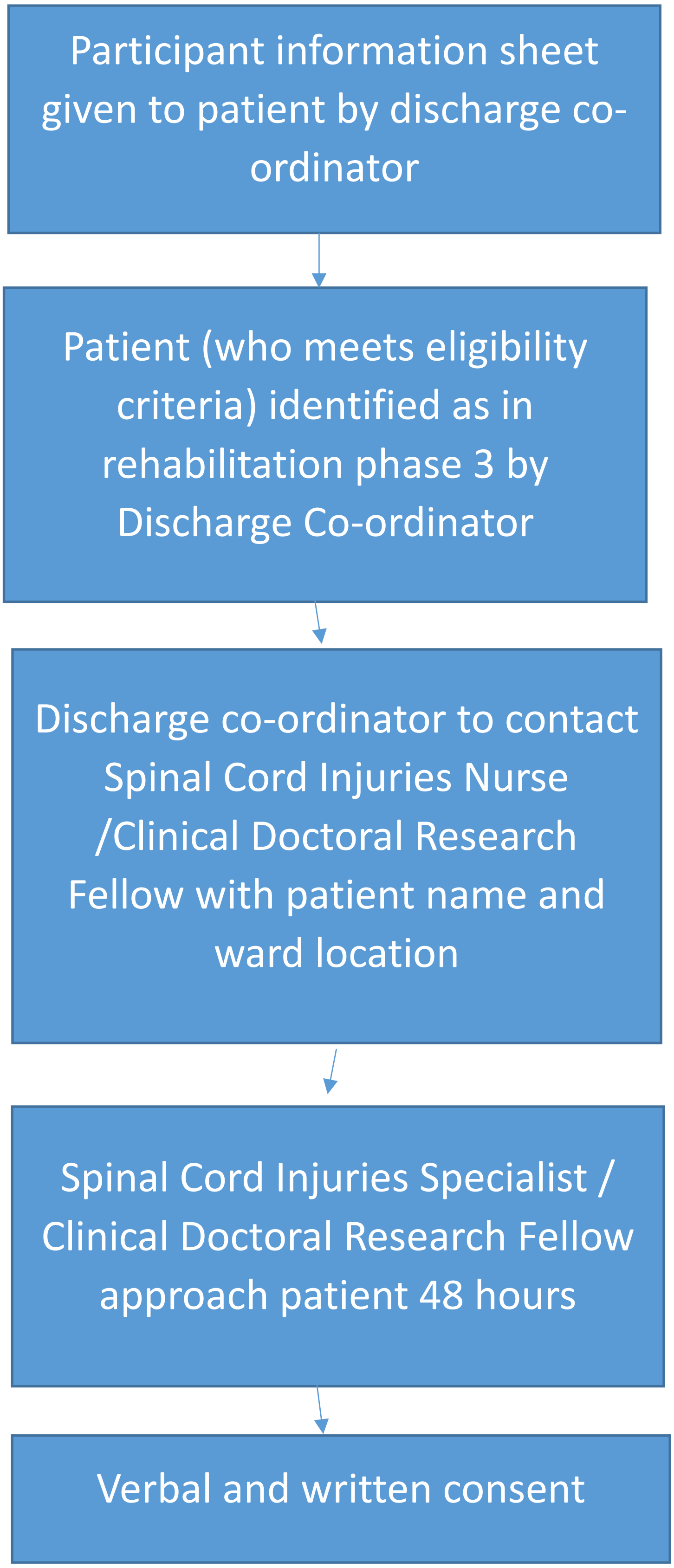


Figure 4.1: Schematic of recruitment process of patients

4.5 Material

As discussed in Chapter 2, pressure mapping systems have often been used to provide a “snapshot” of pressure measurements when looking at support surfaces or repositioning strategies. Recently, however, systems have been adapted to allow for long term monitoring. Two such systems which are readily available within the host organisation, are the Foresite PT (Figure 4.2) and Foresite SS (Figure 4.3), both systems of which are based on capacitive sensor technology. The former system consists of a fitted mattress cover embedded with 6136 sensor cells, covering a surface area of 762x1880 mm. The manufacturer reports a spatial resolution of 15.9 mm, a calibrated range of 5mmHg-200mmHg and an accuracy of +/- 2mmHg (XSENSOR 2018a). The Foresite SS consists of a fitted wheelchair cover with 1296 sensors covering a surface area of 457x457 mm, a spatial resolution of 12.7 mm, a calibrated range of 5mmHg- 200 mmHg and an accuracy of 5% (XSENSOR 2018b). Both systems continuously monitor the body surface pressure profiles and display real time images on a touch screen monitor. Up to 72 hours of continuous data can be collected and stored for subsequent analysis. An external 18,000 MAH battery is attached to the wheelchair system in order to power the system for 12 hours while the participant is mobile. Images from these monitoring systems are downloaded and analysed using Pro-v8 and PT analyser software, respectively.

The set up for the continuous pressure monitoring system (CPMS) was different for measurement on the mattress and wheelchair cushion. The pressure mat designed for the mattress was placed on top of the participants support surface, underneath a bed sheet. The device was secured to the mattress using corner attachments and weighted side straps were used to ensure its secure positioning. Data from the device was streamed at 1Hz via a wire to a tablet monitor which was plugged into a wall. By contrast, the pressure mat placed on the wheelchair cushion needed to be mobile to accommodate patient transitions between wards and rehabilitation areas. The seating device was placed on the wheelchair cushion, the mat connected wirelessly to a tablet monitor. This tablet was attached to an external battery which powered the system and enabled monitoring for up to 12 hours. The monitor and the battery were placed in a wheelchair backpack for convenience. For the more active participants, removable Velcro was required to secure the pressure mat to the wheelchair cushion.

Figure 4.2.: Foresite PT system to monitor pressures continuously in a bed environment

Figure 4.3: Foresite SS system to monitor pressures continuously in a wheelchair environment

4.6 Test protocols

The period of pressure monitoring was used to achieve objectives outlined in Figure 4.4. First, as part of the intervention it provides attending clinicians with visual evidence of the everyday routine and lifestyle of each participant. The data extracted from the monitoring technologies will indicate the period of time the participant spends on the bed or in the wheelchair, the frequency and magnitude of pressure relieving movements, the magnitude of peak pressures and the pressures over “high risk areas”. The analytical approach for defining these parameters is detailed in section 4.7.

In addition, the pressure monitoring system provides biofeedback to the participants. An important aspect of PU prevention is health behaviour, which is particularly relevant for participants who are in phase 3 of their rehabilitation. At this stage, patients have generally reached a level of independence in their everyday activities, which requires them to “self-manage” their PU prevention strategies. Long term patient monitoring can be used to examine their “high risk” areas, peak pressures, pressure relieving activities, and how long they can maintain their postures in bed or in a wheelchair. This feedback can be explained to the patient and used to prescribe the recommendations established within an individual

Long term pressure monitoring will also provide useful quantifiable data. This can be used to assess the potential of the monitoring to assist in improving pressure ulcer prevention behaviour. Outcome measures will include frequency, magnitude and duration of movements, with particular reference to temporal values of displacement of centre of pressure, contact area and peak pressures.

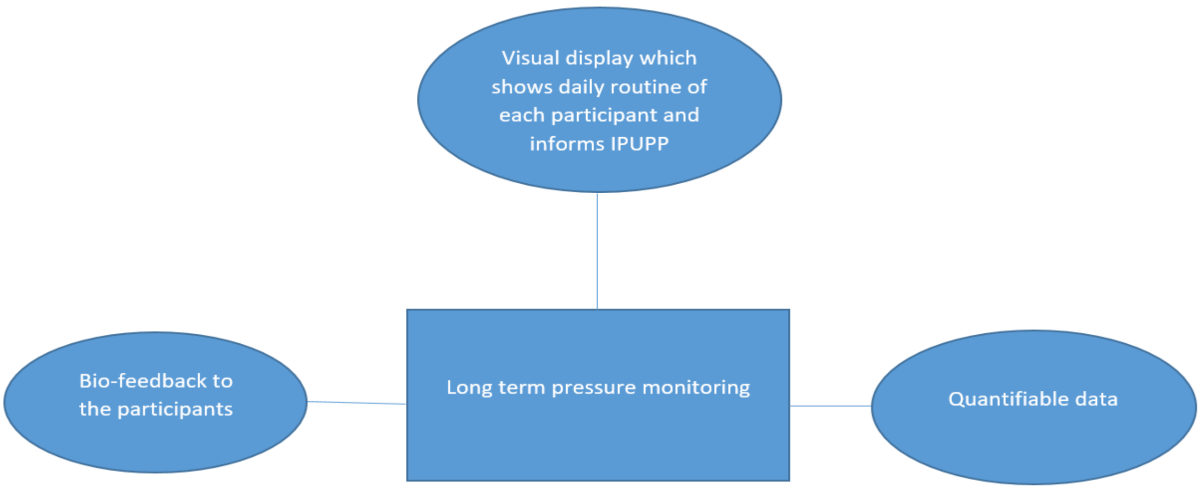


Figure 4.4: Schematic representation showing three objectives of long-term pressure monitoring

The Clinical Doctoral Research Fellow (CDRF) checked the participant's skin on three occasions each week during the inpatient phase of the study. After the participant had been discharged to the community, skin checks were clearly influenced by the COVID 19 pandemic. In particular, skin checks were performed when the participants were comfortable with the CDRF carrying out the examination. However, information from participants and carers were documented during this phase of the study to minimise contact that was not clinically essential. Findings were documented on the Pressure Ulcer Prevalence Sheet (European Pressure Ulcer Advisory Panel 2002), which is shown in Appendix 2. Recorded incidence of skin marking during the rehabilitation phase will provide one of the secondary outcome measures.

4.6.1 Individualized Pressure Ulcer Prevention Plan

The IPUPP represents a clinical document which describes the recommendations set out by the Clinical Doctoral Research Fellow and other members of the participant's clinical team (Appendix 1). This document remained at the patient bedside in the nursing notes to acquaint the clinical staff to follow and a separate copy was kept for each participant.

As previously highlighted in reviews (Tung et al., 2015; Regan et al., 2009) there is often a considerably variability in responses between patients presenting with an SCI or CES. This can be attributed to both the level and severity of the spinal injury, which can result in significantly different physiological outcomes. In addition, there are inherent variations associated with co-morbidities, age and lifestyle activities. Therefore, it is unrealistic to create plans for PU prevention which will be generalizable for the entire target population. The IPUPP will be designed to accommodate those individual factors. As there is no recognised format to follow, information derived from participant interviews, analysis of initial pressure monitoring data and skin checks were all integrated coupled with clinical judgement to formulate the individual IPUPP.

Based on data collected from the monitoring technologies for periods in both bed and in the wheelchair, recommendations would be made with reference to:

- Support Surfaces (wheelchair cushion and mattress)
- Time spent in wheelchair
- Pressure relieving movement techniques
- Interval profiles for pressure relieving movements
- Turning technique while in bed

- Turn interval while in bed

In particular, specific recommendations would include:-

- Decreased/Increased time spent in wheelchair,
- Increase/decrease in frequency of turning in bed

Implementation of regular pressure relieving activity. The plan was monitored/ reviewed at the three time-points previously described

4.6.2 Interviews to elicit patient perspectives on barriers and facilitators to use of the IPUPP

These interviews served to gain patient perspectives on continuous pressure monitoring. Responses from the interviews were used in a directly applied clinical context to inform the IPUPP. Patient perspectives were collated during timepoint 1 and, where appropriate timepoint 2, during their inpatient care. However, due to restrictions and difficulties created by COVID in terms of access to each participant, interviews were not utilized in the community as originally planned. Therefore, interviews are included in the case studies presented in Chapter 5 and 6.

4.7 Measures

The primary outcome measure of this study is the frequency of pressure relieving movements in a cohort of spinal cord injured patients. This outcome measure is relevant at all timepoints

The following parameters are essential in identifying pressure relieving movements:

- Peak pressure values.
- Contact area
- Centre of pressure
- Skin status

Figure 4.5 details the process for identifying pressure relieving movements

4.8 Data analysis

Quantitative data was collected and analysed using EXCEL software. Pressure data from each sensor was sampled at 1Hz. From a clinical perspective, it was essential to identify types of macro movement which could be conducive to complete off-loading of pressure from vulnerable tissue areas. The first stage of the process was to reduce the acquired data to manageable amounts for clinical observation. This was achieved by reducing the data by a factor of 300 to one frame every 5 minutes in the lying position, and by a factor of 120 to one frame every 2 minutes in the sitting position (Coggrave and Rose 2003). Movements were identified by translating numerical data relating to peak pressure, contact area and centre of pressure into a graphical format. Movements were identified, when peaks and troughs in activity correlated in at least two of the pressure-related parameters. These movements were then verified by visually examining the temporal body map feedback provided by the PRO V8 software. It became evident that with respect to the pressure-related parameters, contact area and centre of pressure demonstrated the highest rate of accuracy when indicating defined movements. A definition of MOVAs is provided below (Table 4.1).

4.8.1 Movement to Off-load Vulnerable Areas (MOVA)

Movements prescribed to off-load vulnerable areas, termed MOVA, was defined in Table 4.1 for both lying and sitting. Generally, the vulnerable areas would include the sacrum and ischial tuberosities, respectively. However, specific areas may also be apparent in individuals, for example, where previous tissue damage had occurred. MOVAs are often initiated by nursing staff, for example in the use of the use of the 30° side-lying position (Woodhouse et al. 2019), although suitable PWSCI are encouraged to become more independent and move themselves in the later stages of rehabilitation. The process for identifying MOVAs are

Table 4.1 Definition of MOVAs

Movement to Offload Vulnerable Areas (MOVA)	
Mattress	***Wheelchair cushion***
Left side lateral	Lean forward in chair > 2 minutes
Right side lateral	Push up in chair > 2 minutes
Lying on back	Left or right side lean > 2 minutes

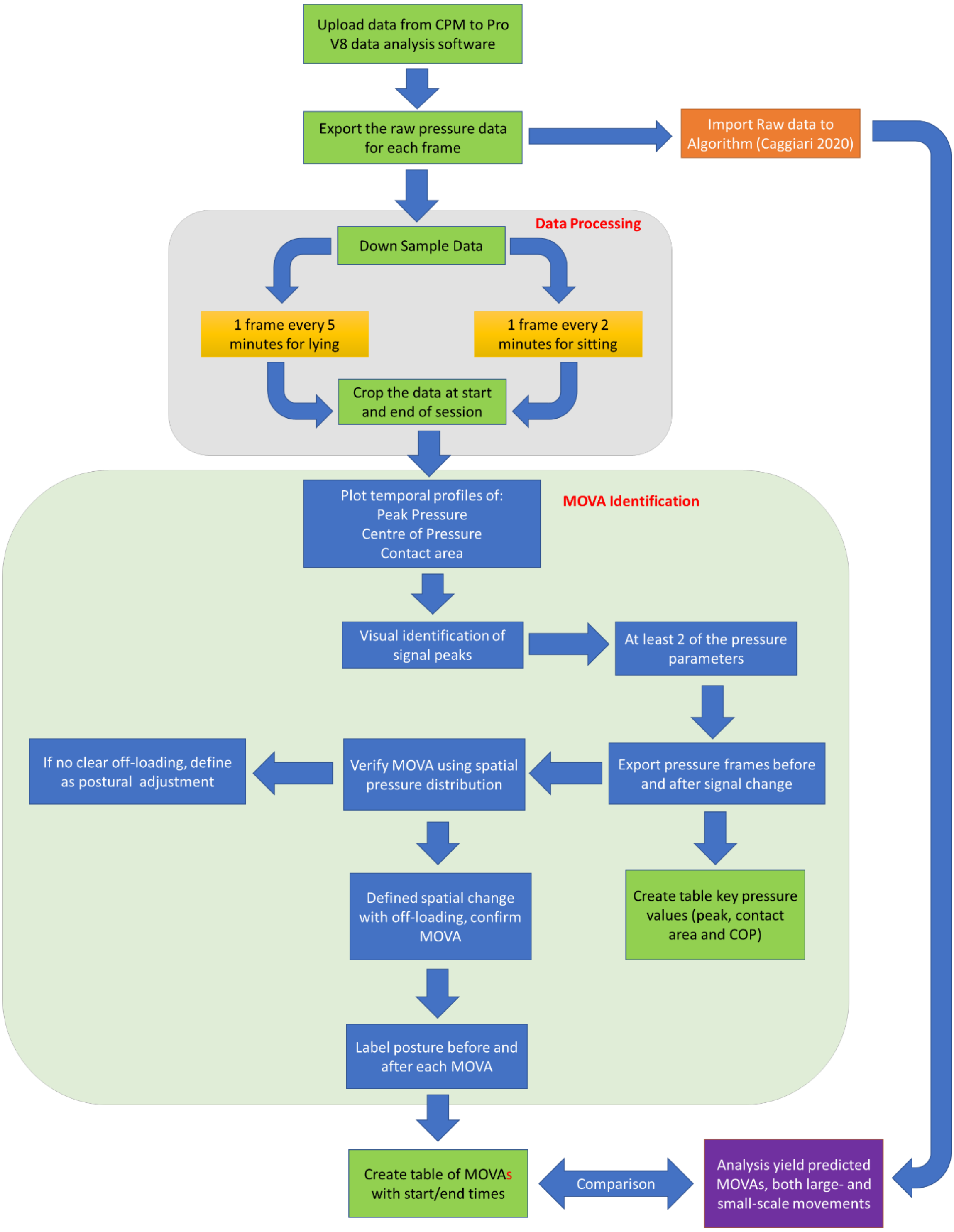


Figure 4.5: Schematic outlining process for identifying movement to offload vulnerable areas

4.8.2 Statistics

As identified in chapter 2, there is a paucity of evidence examining the relationship between level or severity of injury and pressure relieving movements. Therefore, in order investigate the relationship between pressure relieving movement and intrinsic factors of SCI, two parameters were identified; i) the average number of MOVAs and ii) maximum time between MOVAs. The trends between patient characteristics (injury level and ASIA score) and MOVA profiles were assessed using histograms and crosstabulation. Comparison of clinical interpretation and algorithm prediction was also made using Pearson's correlation coefficients, with significance prescribed at 5% ($p<0.05$). Descriptive statistics were used to explore movement trends in SCI participants who had episodes of skin damage with respect to those with no skin damage

4.8.3 Algorithm

In conjunction with the clinical observation approach, an algorithm has been developed and published as part of a bioengineering PhD project conducted in the host Department (Caggiari et al. 2019). This algorithm uses signals from the pressure-related parameters, such as centre of pressure (COP) and contact area, which were identified to be sensitive and specific to movements in the bed and chair (Caggiari et al. 2019). The algorithm creates patient specific thresholds for movement based on the derivative of these pressure parameters, with data classified through machine learning (Caggiari et al. 2020). The algorithm detects both large scale and small-scale movements. This algorithm was compared to case studies of the SCI cohort from the present study (Chapter 5), where correlations were observed between nursing interpretation and algorithm predication. However, it was of note that the algorithm provided a higher level of sensitivity, particularly to smaller scale movements (Caggiari et al. 2021).

4.9 Governance and ethical approval

Institutional approval was obtained from University of Southampton to sponsor the study (ERGO number: 41814). Ethical approval for the patient study was applied for using the Integrated Research Application System (IRAS). Approval has been granted from Health Research Authority and Research Ethics Council (IRAS number: 245580). Confirmation of capacity was confirmed by Salisbury NHS Foundation Trust on 2nd November 2018.

All patient identifiable information was anonymised before being taken from the hospital for analysis. Clinical staff will be able to access patient identifiable information from the secure password-protected server at Salisbury District Hospital. Anonymised information was accessed by other members of the research team via an encrypted USB, provided by Salisbury District Hospital. The encrypted USB will be kept in a locked office in the Clinical Academic Facility at Southampton General Hospital. Baseline care was not affected during this study.

Chapter 5 Timepoint 1 results- Initial assessment of posture and mobility in the spinal cord injured inpatient cohort

This chapter presents the results from the continuous pressure monitoring at timepoint 1. At this time, usual practice was followed for pressure ulcer prevention strategies, through education and advice from the multidisciplinary team. This chapter will provide reference data from which comparisons can be made in subsequent chapters, where the intervention has been delivered (Chapter 6) and the spinal cord injury (SCI) patients are transferred to the community (Chapter 7).

5.1 Participants

A total of 12 participants were recruited into the study over a 13 month period (December 2018-Jan 2019). Their demographics, as detailed in Table 5.1, reveal a wide range of ages, level of injury and ASIA scores, which include A, B and D. The participants presented with a range of co-morbidities, some of which can influence their susceptibility to skin damage e.g., diabetes myelitis (P9).

Table 5.1: Participant demographics and co-morbidities

ID	Age years	SCI Level	ASIA	BMI (kg/m^2)	Co-morbidities
P1	64	T6	A	27	Cardiac Surgery
P3	75	T5	A	28	Osteoarthritis and mitral regurgitation
P4	77	T10	A	28	Thoracic AVF and Pulmonary embolism
P5	66	T11	D	24	Aortic Fistula and bi-iliac aneurysm
P8	70	T4	D	30	Dermatitis, asthma, hypertension
P9	53	C4	A	27	T2 DM, High cholesterol
P10	74	T11	A	21	Arthritis, high cholesterol and prostate removed
P11	27	C4	B	21	Asthma
P12	18	L2	B	Unavailable. Athletic build	ADHD, Hyper reflexivity
P13	53	C5	B	28	Dental Abscesses
P14	29	C8	B	25	Epilepsy
P15	30	T11	A	22	No

Each participant was prescribed a support surface based on their risk of developing a pressure ulcer. Braden score's (Table 5.2) ranged from values of 6 to 24, the former representing the highest level of risk. Braden scores have been included as they are a skin-related assessment routinely collected as part of clinical care. Decisions to utilize an air mattress in this particular spinal cord injury centre

(SCIC) were not based on Braden score, but clinical judgement. For example the patient with the lowest Braden score (P11) was not prescribed a high specification air mattress during inpatient care. Table 5.2 also includes information regarding the participant's history of bed rest due to skin damage. Following a review of their past clinical notes, five of the participants (P1, P3, P5, P9 and P13) had presented with skin damage, in the form of pressure ulcers (PUs), moisture associated skin damage (MASD) and traumatic abrasions that did not readily heal. It notable that only two of the participants (P1 & P9) who were previously placed on bed rest due to skin damage, were prescribed an air mattress, which is associated with the highest levels of immersion and thus an effective means of pressure redistribution. All other participants were given castellated or non-castellated foam mattresses during their inpatient stay. In addition, for sitting in wheelchair, three participants (P9, P13 and P14) were prescribed air-based cushions. All other participants used foam/gel cushions.

Table 5.2: Participant support surface and skin specific features at timepoint 1.

ID	Braden (6-24)	Wheelchair Cushion	Mattress	History of bed rest
P1	14	Jay 2- Fluid/Foam	Talley Quattro -air	Yes
P3	15	Jay balance- foam/fluid	Softform Spinal- non castellated Foam	Yes
P4	17	Invacare Matrx Foam	Softform Spinal- non castellated foam	No
P5	17	Matrx Libra cushion-foam	Softform premier – castellated foam	Yes
P8	16	Matrx Contour -foam	Softform spinal-non castellated foam	No
P9	16	Jay 3 with Roho insert-foam/air	Talley Quattro-air	Yes
P10	15	Matrx Libra-foam/fluid	Softform premier – castellated foam	No
P11	12	Matrx Libra-foam/fluid	Softform spinal –non castellated foam	No
P12	19	Mercury 300 gel	Castellated foam	No
P13	15	Starlock-air	Softform spinal- non castellated foam	Yes
P14	17	Roho Hybrid elite – air	Softform premier- castellated foam	No
P15	19	Matrx Libra-Foam	Softform Spinal - non castellated foam	no

Each participant was monitored for a maximum of three time points, which included an assessment in the bed and chair. These included:

1. Timepoint 1, (phase 3 or 4 of rehabilitation), inpatient prior to intervention using the individualized pressure ulcer prevention plan (IPUPP).
2. Timepoint 2, in-patient follow-up.
3. Timepoint 3, after discharge to the community.

A summary of the completed assessments for each participant is detailed in Table 5.3. The vast majority of participants (12/13) were monitored in the bed and chair for at least two periods in the hospital and/or the community. It evident that only 4/12 participants were assessed twice in hospital i.e. timepoints 1 and 2. This was mainly due to an accelerated discharge process from March to July 2020 to accommodate management of in-patients during COVID 19 pandemic. Further assessments in the community were undertaken in the 4-month period (September to December 2020), after which they were stopped due to the national restrictions amid increased local risk from COVID 19. Patients were monitored for a minimum of 24 hours and a maximum of four days. The duration of monitoring was affected by both patient preference and therapy needs.

Table 5.3: Summary of the monitoring periods during the day and night for each participant during timepoints 1-3.

ID	Timepoint 1		Timepoint 2		Timepoint 3	
	Nights	Days	Nights	Days	Nights	Days
P1	4	2	4	2	2	2
P3	4	-	-	-	-	-
P4	3	2	2	2	2	1
P5	1	1	-	-	2	1
P8	2	2	-	-	2	1
P9	2	2	2	1	-	-
P10	1	2	2	1	2	-
P11	2	1	-	-	2	1
P12	2	1	-	-	2	-
P13	2	1	-	-	2	1
P14	2	1	-	-	2	1
P15	1	-	-	-	2	1

Continuous pressure monitoring data was assessed by the researcher, evaluating key trends and perturbations in the pressure parameters (Section 4.8.1). Given the vast amount of data derived from each assessment period, detailed results are provided from three selected case studies are provided below.

5.2 Timepoint 1 case studies

The method of analysis detailed in the case studies presented below was employed for all participants. A summary of pressure distribution data relevant to each movement to offload vulnerable areas (MOVAs) is provided, with corresponding pressure data from each individual. The three case studies represent a range of spinal injuries from low incomplete (P5 - T11, ASIA D) to high complete injury (P9 - C4, ASIA A). Each case was cared for on different support surfaces.

5.2.1 Participant 5

P5 was 66 years old at the time of monitoring, which took place in July 2019. She was 6 months post injury at T11 level and was assessed as ASIA D. This indicated that sensation and motor function was present at all levels, although motor power was still impaired. She was not walking independently at the point of assessment and was spending up to 4 hours in a wheelchair. The participant had intact sensation and power in their upper limbs and was able to both reposition herself in bed and self-transfer to a wheelchair. She had a BMI of 24 kg/m^2, presenting with cardiac co-morbidities, including Aortic Fistula and Bi-iliac Aneurysm.

Skin assessment

The participant had a history of Moisture Associated Skin Damage (MASD) on her ischial tuberosities which resolved with bed rest. At the time of assessment, there was no skin damage.

Support surfaces and transfers

Pressure monitoring occurred on a castellated foam mattress (Invacare Softform Premier) whilst in bed and a foam/gel cushion (Matrx Libra) in sitting. Due to participant preference, P5 was pressure monitored for one night and one day as detailed in Table 5.4.

Table 5.4: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1.

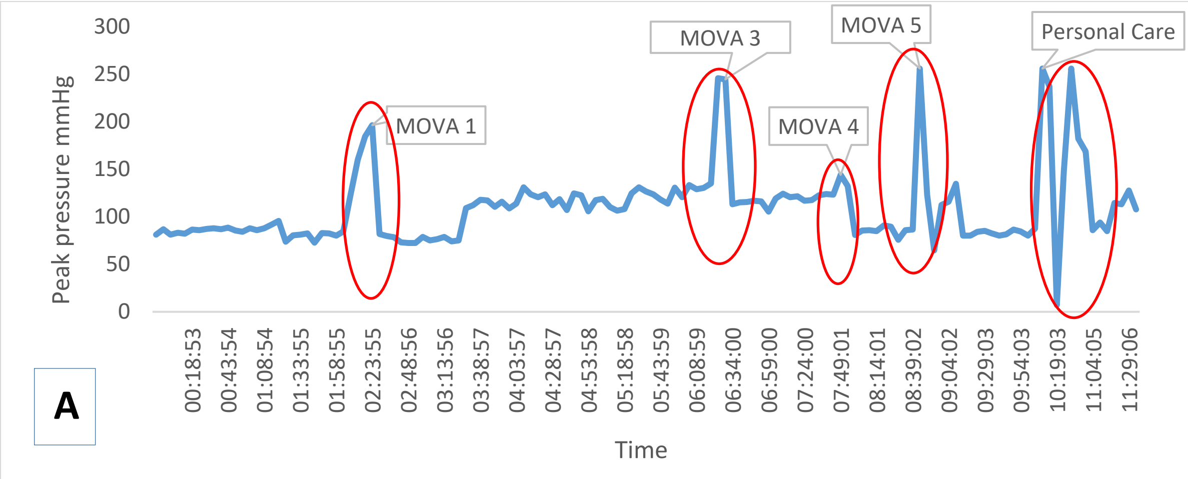
Night	***Time monitoring started***	***Monitoring period on mattress (mins)***	***Number of MOVA***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	21:18:41	878	6	35	130
Day	***Time monitoring started***	***Monitoring period on cushion (mins)***	***Number of MOVA***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	11:04:17	537	2	53	280

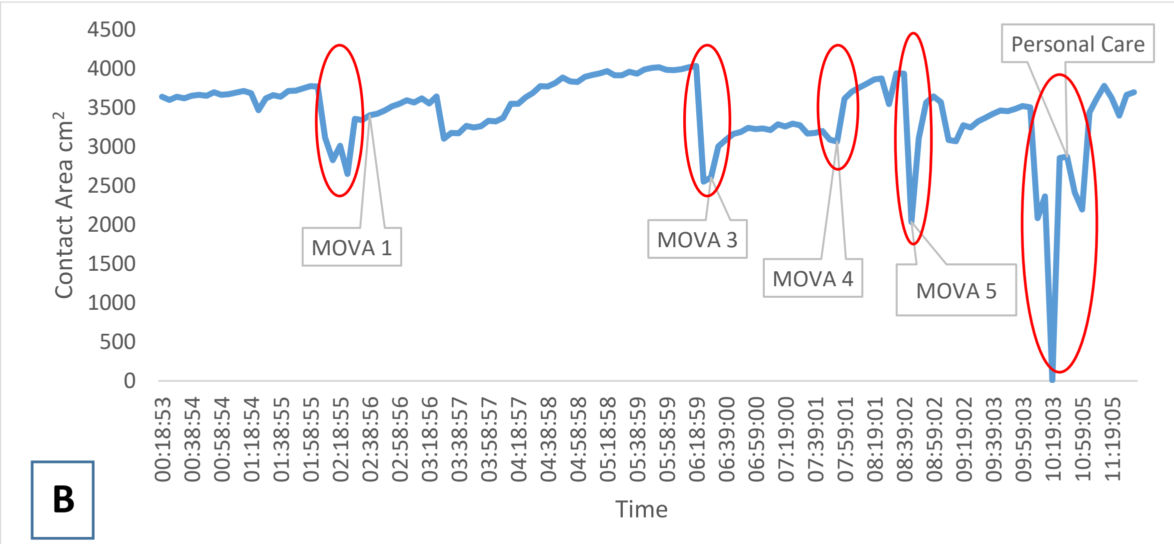
5.2.1.1 Monitoring lying data (night 1)

P5 was monitored for 14 hours and 38 minutes on night 1. There was an extended period of 2 hours 35 minutes, where P5 was particularly active while preparing for sleep. This period was excluded from the data presented in Figure 5.1. It was evident from the temporal profiles of each of the three pressure parameters that P5 turned herself frequently, with static periods ranging from 35 to 130 minutes in duration. Table 5.5 indicates six distinct movements, each identified through perturbations in pressure parameters, highlighted in Figure 5.1, with distinct turns to lateral lying postures or personal care events. The corresponding contour plots of pressure distribution are presented in Figure 5.2-5.7, for each MOVA episode.

Table 5.5: Summary of movements on night 1 of timepoint 1 for P5, as determined by continuous pressure monitoring on foam mattress.

MOVA	**Time since previous MOVA (*mins*)**	**Time started**	**Duration (*mins*)**	**Description of movement**
1	130	02:03	30	Supine > Left side Lateral
2	90	04:03	10	Left side Lateral> Supine
3	125	06:18	15	Supine > Left side lateral
4	70	07:54	5	Left side Lateral> Supine
5	40	08:39	20	Supine> Supine
Personal Care	60	09:59	60	Supine > Supine
Transfer	35	11:34	23	





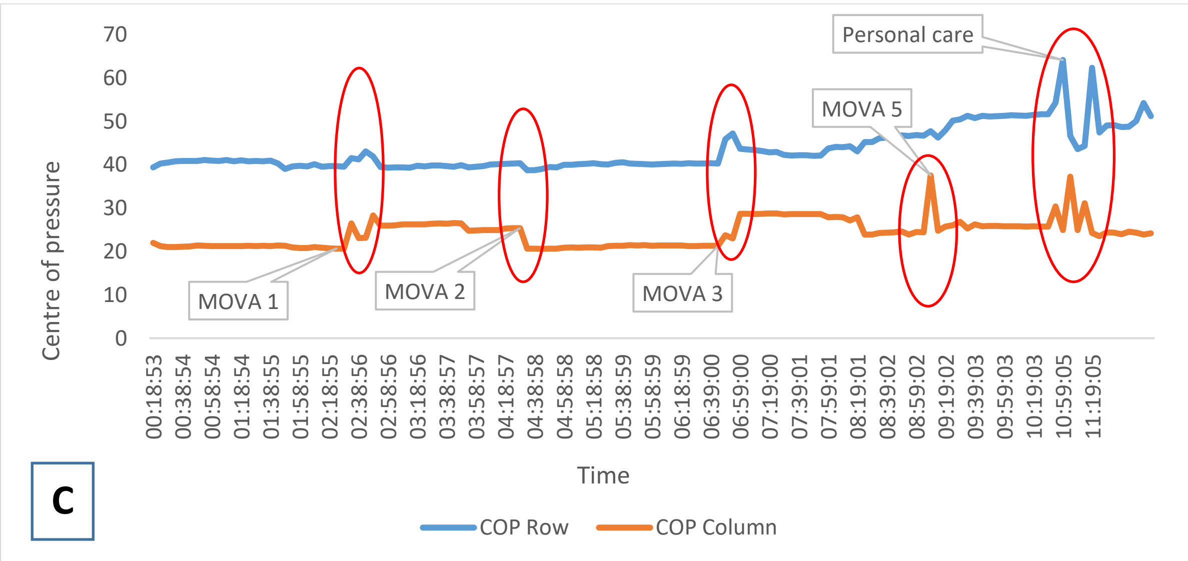
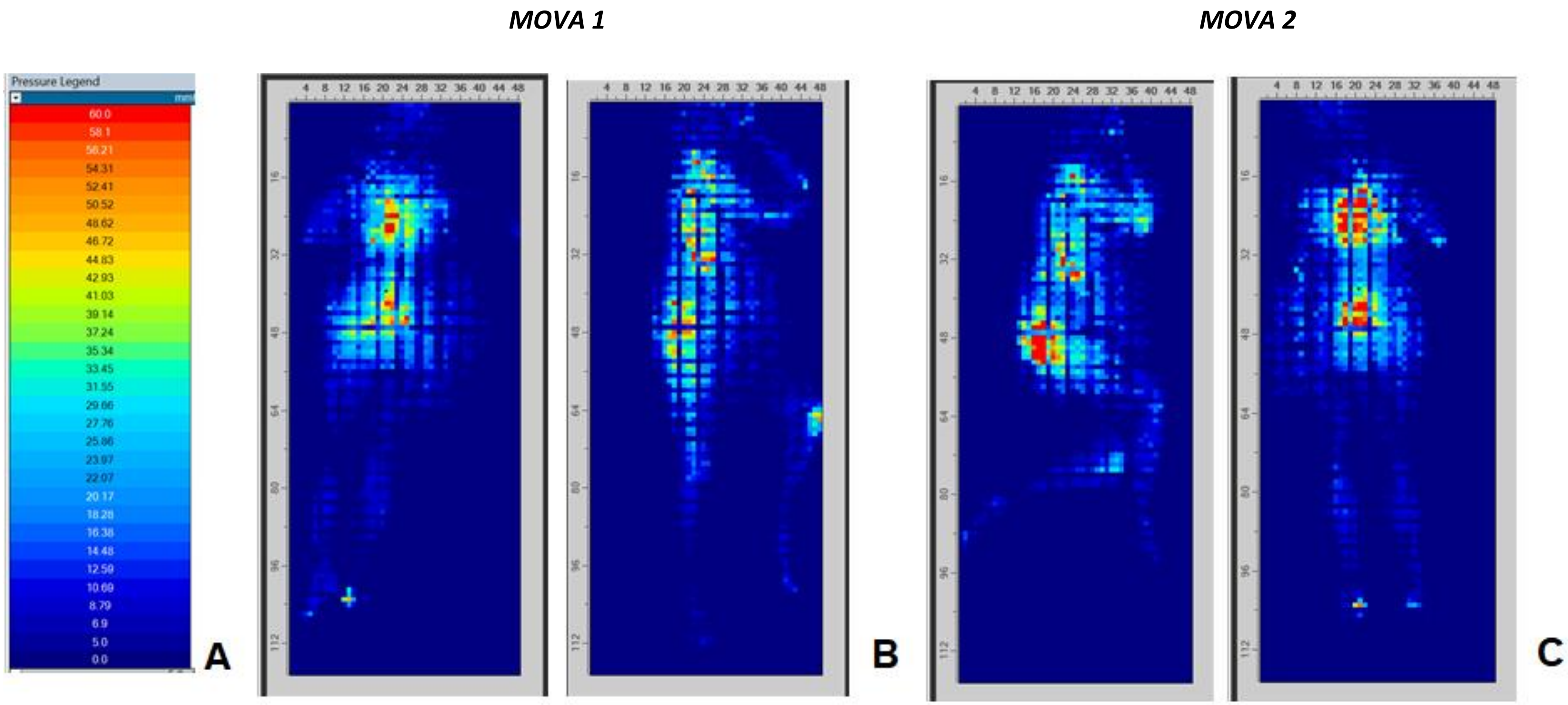


Figure 5.1 : Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure for P5 at timepoint 1, during the first night of pressure monitoring on a castellated foam mattress.

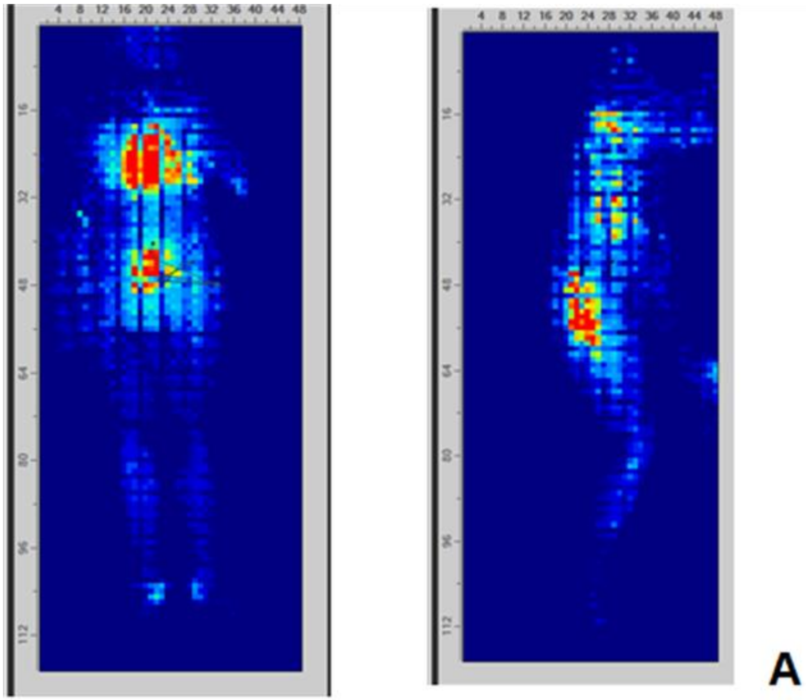


Time	Peak Pressure (mmHg)	Contact Area (cm^2)	COP Row	COP Column
02:03	80	3772	39	20
02:33	80	3394	39	26

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	COP Row	COP Column
04:03	109	3329	40	25
04:13	112	3513	38	20

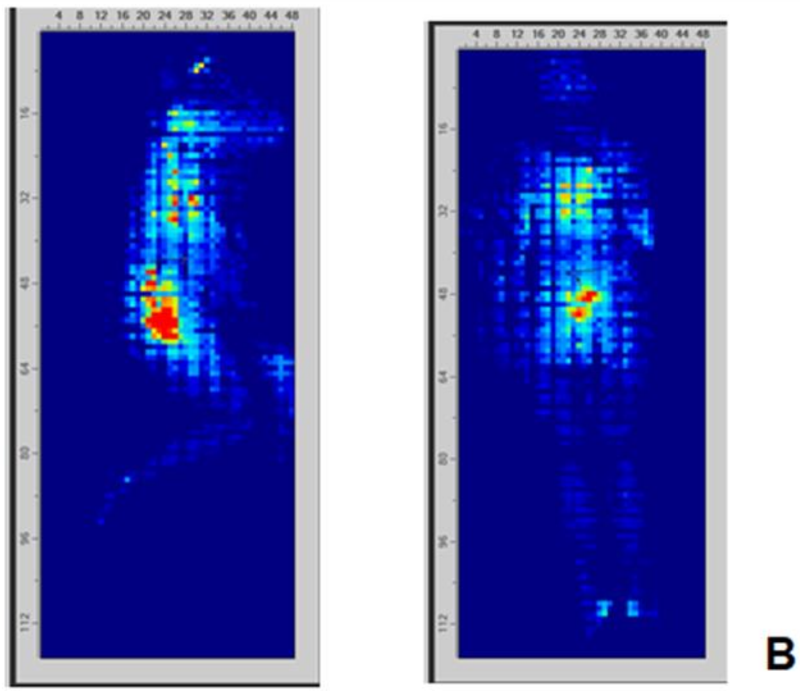
Figure 5.2: (A) Pressure scale depicting the pressure values ranging from 0 - 60mmHg. Pressure distributions and corresponding pressure parameters for (B) supine to left side lateral during MOVA 1 (C) Left side lateral to supine during MOVA 2. Magnitude of the four pressure parameters are also indicated.

MOVA 3



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	COP Row	COP Column
06:18	122	4042	40	21
06:34	113	3004	43	28

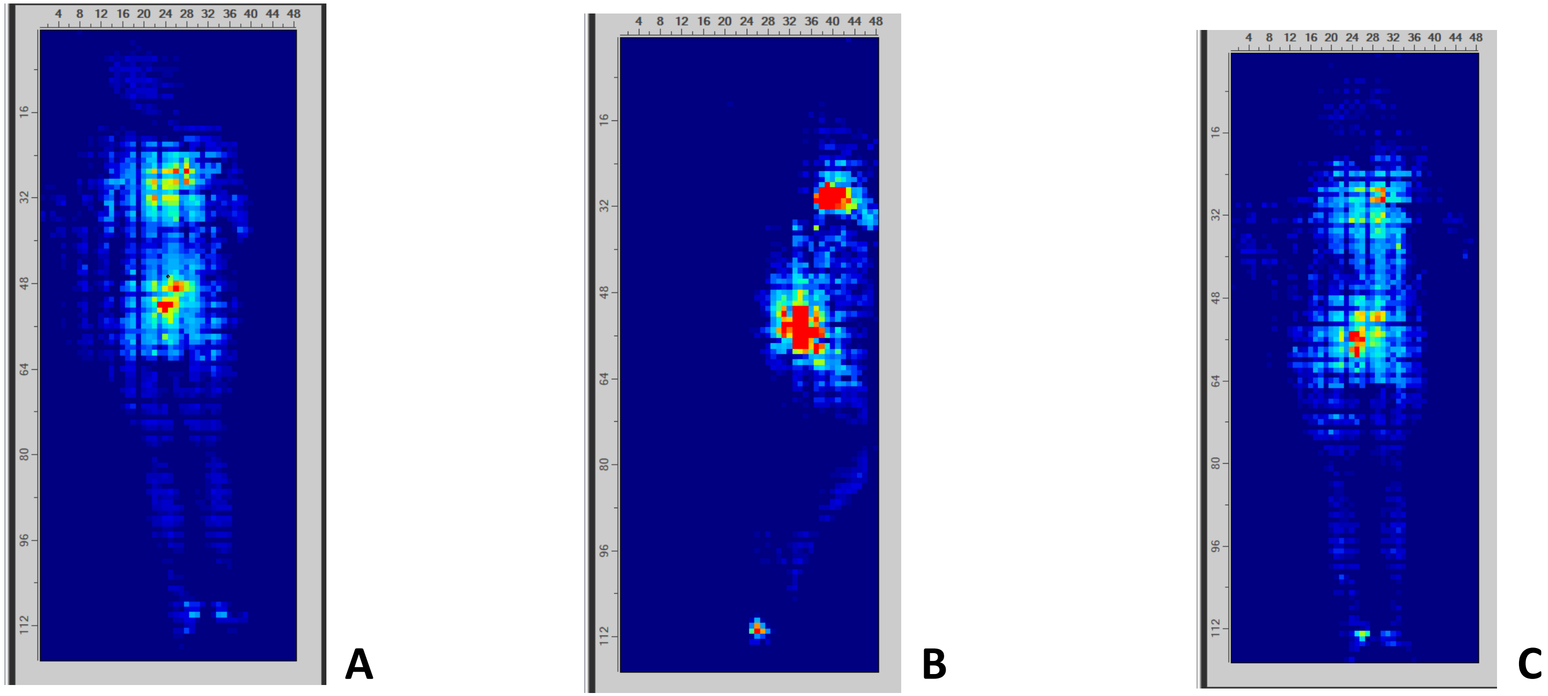
MOVA 4



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	COP Row	COP Column
07:54	132	3062	43	27
07:59	80	3613	45	23

Figure 5.3: Pressure distributions and corresponding pressure parameters for (A) Supine to left lateral during MOVA 3 (B) left side lateral to supine during MOVA 4. Magnitude of the four pressure parameters are also indicated.

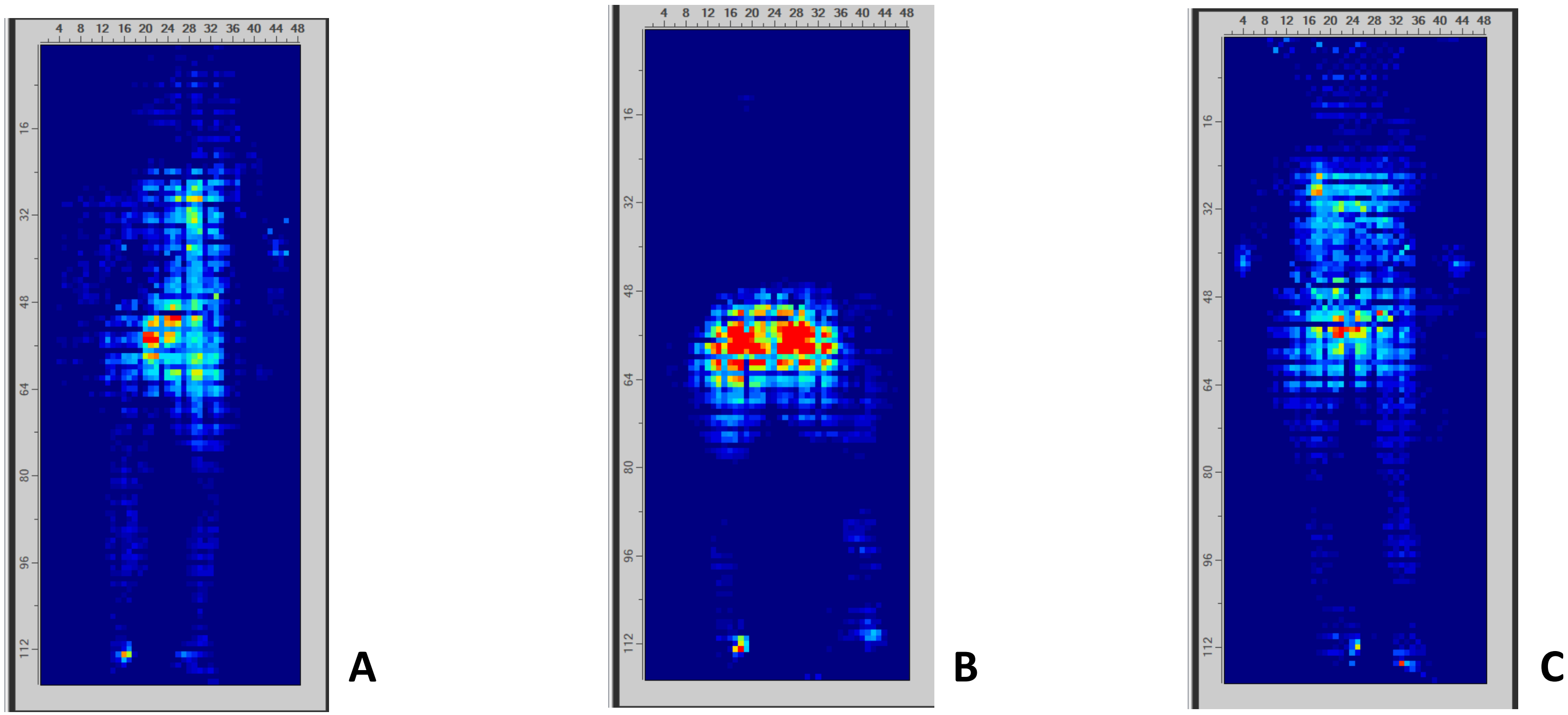
MOVA 5



Time	Peak Pressure (mmHg)	Contact Area (cm²)	COP Row	COP Column
08:39	86	3933	46	24
08:44	255	2121	48	37
08:59	112	3644	50	26

Figure 5.4: Pressure distributions and corresponding pressure parameters for (A) supine (B) left side lateral (C) supine during MOVA 5. Magnitude of the four pressure parameters are also indicated.

Personal Care



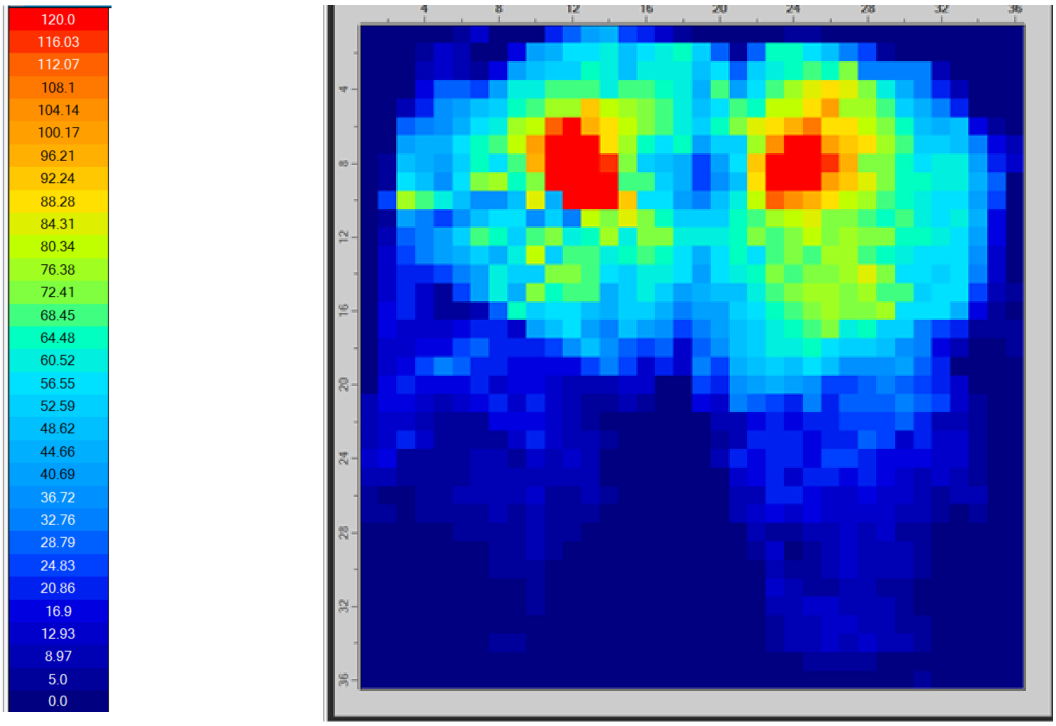
Time	Peak Pressure (mmHg)	Contact Area (cm^2)	COP Row	COP Column
09:59	80	3518	51	25
10:54	201	2348	62	24
11:14	84	3777	48	24

Figure 5.5: Pressure distributions and corresponding pressure parameters for (A) Supine (B) sitting up (C) supine during personal care. Magnitude of the four pressure parameters are also indicated.

The pressure profiles detailed in Figure 5.2-5.4, correspond to a movement from supine to left lateral (MOVAs 2-5). The resulting peak pressure areas move from that at the sacrum and thoracic spine (supine) to the greater trochanter and left shoulder (left lateral). The peak pressure values are similar between postures, although it is evident that the contact area decreased in lateral from 3772-3394cm^2 (Figure 5.2). There is also a change in the centre of pressure, indicative of the lateral movement between postures. The castellation in the foam mattress can also be observed in the pressure profiles. MOVA 5 reveals the highest peak pressures (255mmHg) during side lying, although this posture was only adopted for a short duration of 15 minutes.

5.2.1.2 Monitoring seating data

P5 self-transferred to a foam/gel wheelchair cushion. The pressure distribution in the sitting posture, as illustrated in Figure 5.6, reveals a symmetry of pressure distribution with no evidence of sacral sitting or pelvic obliquity. However, there are two clearly defined areas of pressure which exceeded 256 mmHg, corresponding to each Ischial tuberosity (Figure 5.6) it is of note that this represents the maximum pressure recorded in the commercial sensing array.



B

A

Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure Row	Centre of Pressure Column
17:11	256	1479	11	19

Figure 5.6: (A) Pressure scale ranging from 0 – 120 mmHg (B) Pressure distributions in sitting posture for P5. Magnitude of the four pressure parameters are also indicated.

Day 1

P5 was pressure monitored on a foam cushion for a period of 537 minutes. Figure 5.7 revealed a period of time where no pressures were recorded as P5 temporarily transferred off the wheelchair for 40 minutes between 11:33 and 12:13. It is probable that during this period P5 transferred to other support surfaces, such as a shower chair, toilet, or physio plinth. These surfaces are unlikely to off-load the soft tissues adjacent to the pelvic region. Therefore, these periods cannot be considered to represent off-loading within the temporal pressure profile.

P5 moves to the front of the chair, effectively repositioning, on two occasions during the pressure monitoring on the wheelchair cushion (Table 5.6). These periods of repositioning are shown in in Figure 5.7 with clear perturbations in the temporal pressure values. The changes in the spatial distribution of pressure values are depicted in Figures 5.8 and 5.9. Pressure profiles during sitting revealed high peak pressures in excess of 256 mmHg over the ischial tuberosities, which were off-loaded during each MOVA. These movements were maintained for approximately 6-12 minutes, after which the original posture was adopted with similar spatial distributions of pressure. It is notable that pressures regularly exceeded the maximum recordable pressures of 256 mmHg.

Table 5.6: Summary of movement for P5 on day 1 of pressure monitoring on wheelchair cushion.

Movement to offload vulnerable areas	**Time started**	**Duration *(mins)***	**Description**
1	13:59	6	Move forward to front of chair
2	18:55	12	Move forward to front of chair
Monitoring stopped	20:01		

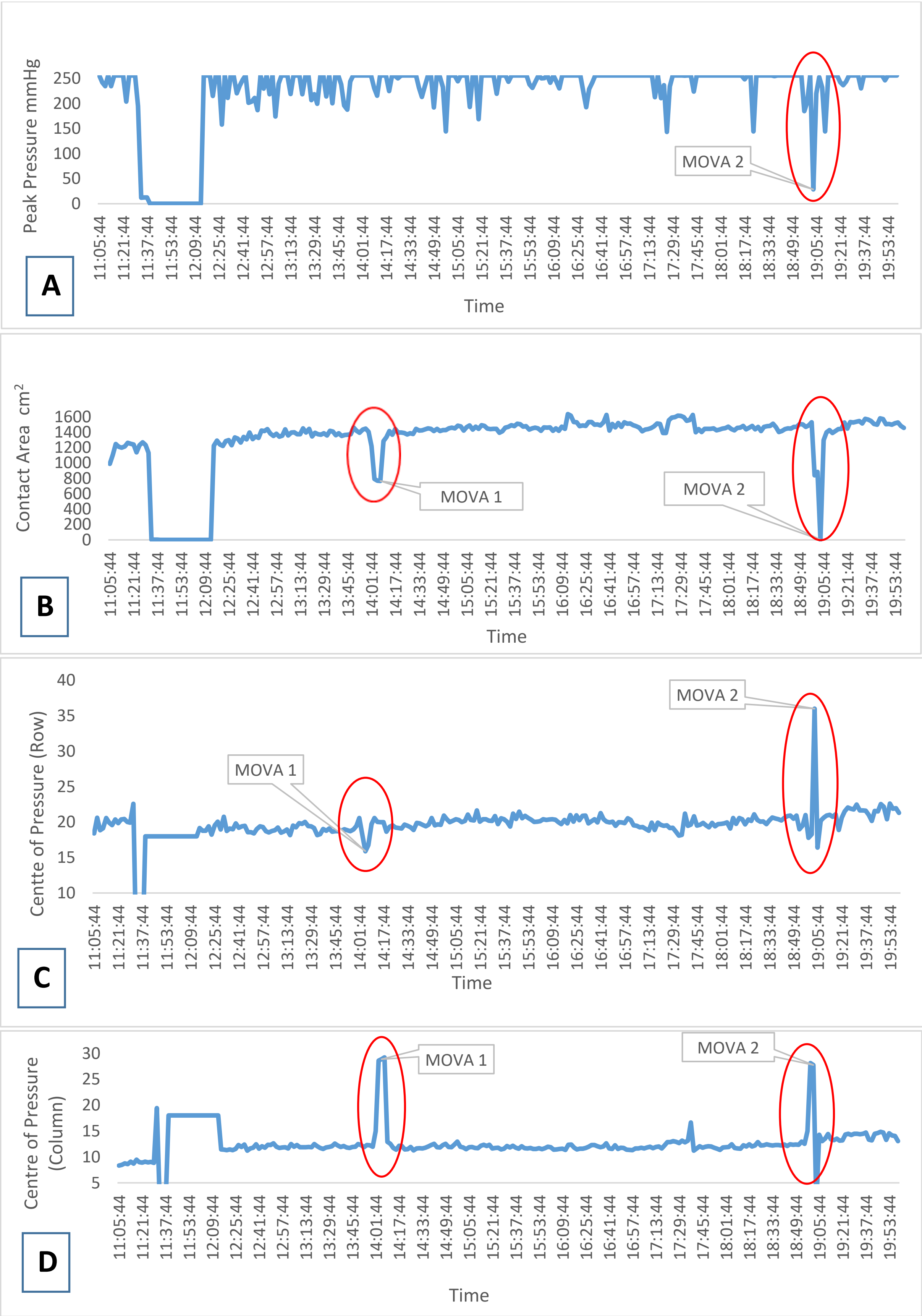
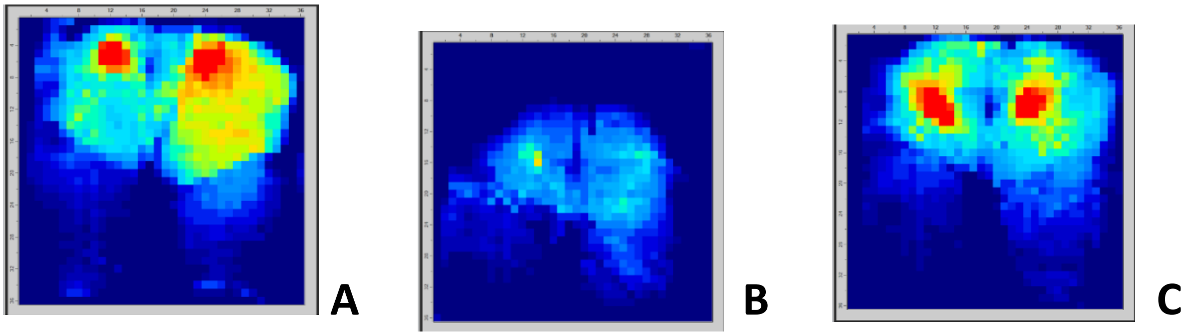


Figure 5.7: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of Pressure, column for P5 on day 1 of pressure monitoring on a wheelchair cushion

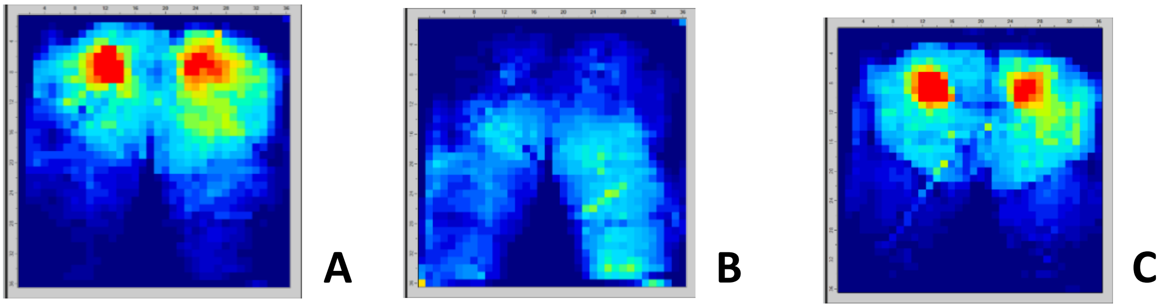
MOVA 1



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
13:59	<256	1399	11	20
14:09	89	920	19	19
14:15	<256	1366	11	19

Figure 5.8: Pressure distributions and corresponding pressure parameters at (A) 13:59 (B) 14:09 and (C) 14:15 during MOVA 1. Magnitude of the four pressure parameters are also indicated.

MOVA 2



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
18:55	<256	1483	12	19
18:58	88	1570	21	19
19:07	252	1404	13	20

Figure 5.9: Pressure distributions and corresponding pressure parameters at (A) 18:55 (B) 18:58 and (C) 19:07 during MOVA 2. Magnitude of the four pressure parameters are also indicated.

Interview

Question: Was there anything P5 liked or disliked about her current pressure ulcer prevention methods?

"*Well just the incontinence pads you know what I mean that's the main issue with me because of, obviously I understand why they are using them, you know what I mean, but more often than not the sheets get soiled anyway and the same with the wheelchairs, do you know what I mean the cushion cover have to come off and everything else. And course it's like heat which makes you sweat more"*

P5 indicates a clear issue with use of incontinence pads for prolonged periods of time. She is suggesting they create moisture which subsequently leads to skin damage.

Question: Was there any factors that might affect P5's ability to carry out PU prevention?

"I mean the thing is, well this is it cause I mean my husband and I you know what I mean, I mean we've always slept together , you know what I mean where as its sort of like at the moment, it will be he's upstairs in the bed, and I'm downstairs in the bed, you know what I mean it's like living two separate, I know we're not , we're still together in the same room but it is , I mean we've always together, all through our married life, you know what I mean , so you know, and I was just thinking well does it mean he's got to get a single bed , so we can push them together or what actually happens do you know what I mean"

It is evident P5 is struggling with the notion of sleeping on a pressure relieving mattress, separated from her husband upon discharge.

P5 went on to say *"well plus the fact that my husbands, he's err retired now, he wasn't but he's take, he taking his retirement now, you know what I mean, so I mean he's always gonna be there, you know what I mean, and my daughters gonna be living , well she's living with us at the moment, but she'll be living around the corner , and she's in the care system, she's been er, you know, worked in a nursing homes and everything and that so he know what's what".*

It can be seen that P5 feels she will have good support after discharge from her husband and daughter

Skin Check

It was noted on the first skin check, that there was redness, blanching and circular marking on sacrum. This mark faded during the skin-check. There was also an evident scar on the left ischium, approximately 50 mm long and 5mm wide, from a previous MASD. No other skin problems were observed.

5.2.2 Participant 9

P9 was 53 years old at the time of monitoring, which took place in October 2019. He was 9 months post injury, which was at the level of C4 and was assessed as an ASIA A with no sensation and motor power below the level of injury. As a result of this high-level injury, he had a significant loss of function, in addition to an epidural abscess. He had a BMI of 27 kg/m^2 and presented with other co-morbidities, including Type 2 DM and high cholesterol.

Support surfaces and transfers

Pressure monitoring was conducted in lying while the patient was supported on an air mattress (Talley Quatro Plus). He was hoist transferred to a wheelchair, where he was monitored while sitting on a foam/gel cushion (J3 deep gel). For repositioning, P9 required assistance of the nursing staff. The patient was monitored for 2 nights and 2 days, with relevant MOVAs detailed in Table 5.7.

Table 5.7: Summary of movement behaviour for P9 on air mattress and wheelchair cushion at timepoint 1.

Night	**Time monitoring started**	**Lying Monitoring period (*mins)***	**Number of MOVA**	**Minimum time between MOVAs *(mins)***	**Maximum time between MOVAs (*mins)***
1	20:27:13	880	2	115	382
2	20:19:15	932	1	392	516
Day	**Time monitoring started**	**Seating Monitoring period (*mins)***	**Number of MOVA**	**Minimum time between MOVAs *(mins)***	**Maximum time between MOVAs *(mins)***
1	12:09:25	499	2	148	206
2	11:51:12	510	0	510	510

Skin Assessment

P9 acquired a grade 2 PU during rehabilitation, which resulted in several weeks of bed rest. Skin checks during time-point 1 pressure monitoring showed no areas of concern, with his previous damage being healed.

5.2.2.1 Monitoring lying data (night 1)

P9 was monitored for 14 hours and 40 minutes on night 1 and a summary of movements is provided in Table 5.8. P9 remained in a static position for periods ranging between 115 -382 mins during the monitoring period. He was positioned in both right and left lateral positions, in addition to lying in supine. The two lateral movements correspond to the changes in the pressure-related parameters, indicated in Figure 5.10. The corresponding pressure distribution values from each MOVA are detailed in Figures 5.11-5.12.

Table 5.8: Summary of movements on night 1 of timepoint 1 for P9, as determined by continuous pressure monitoring on an air mattress.

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	382	02:57	35	Right side lateral > Left side lateral
2	290	08:22	45	Left side lateral > Right side lateral
Transfer off bed	115	11:02	4	

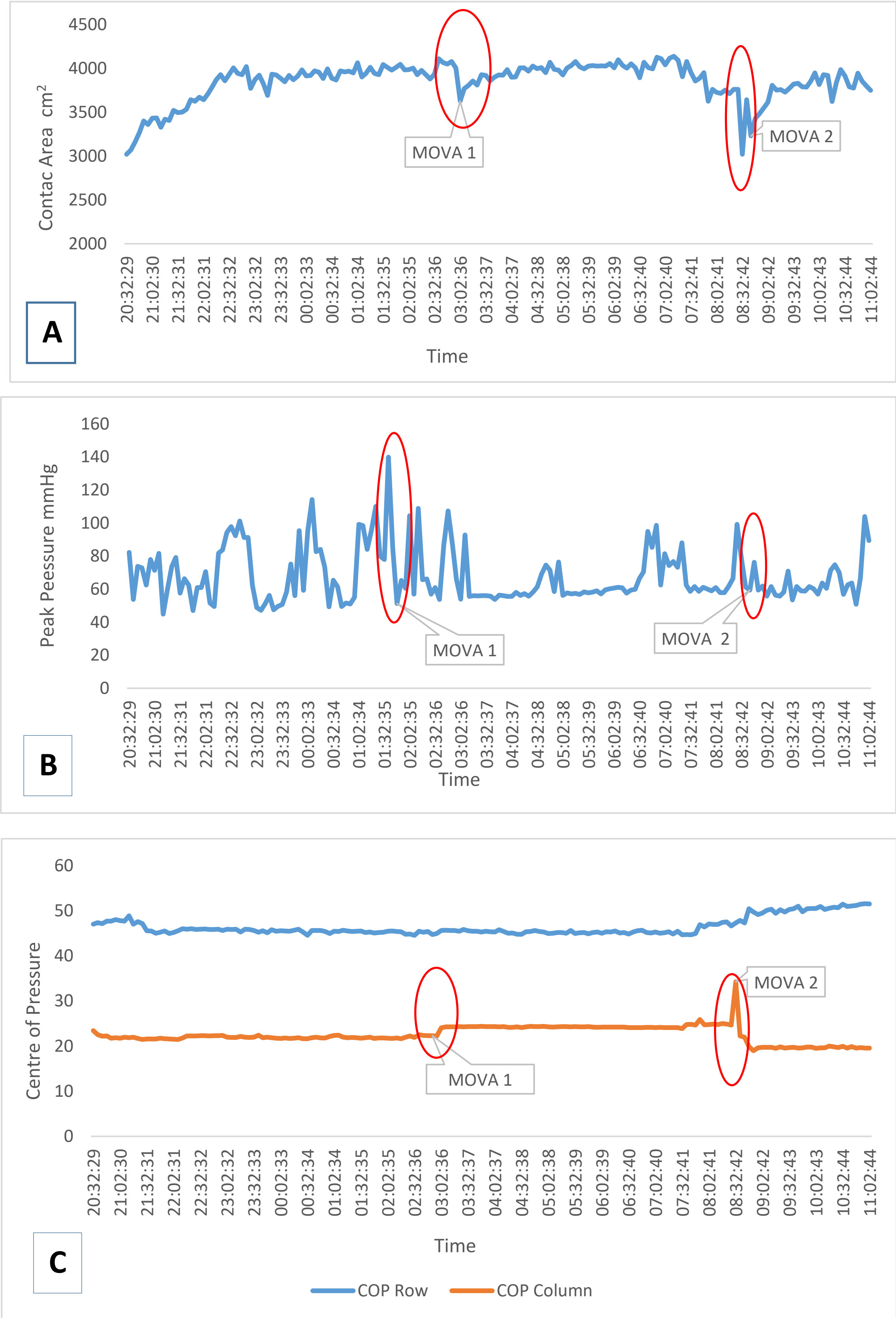
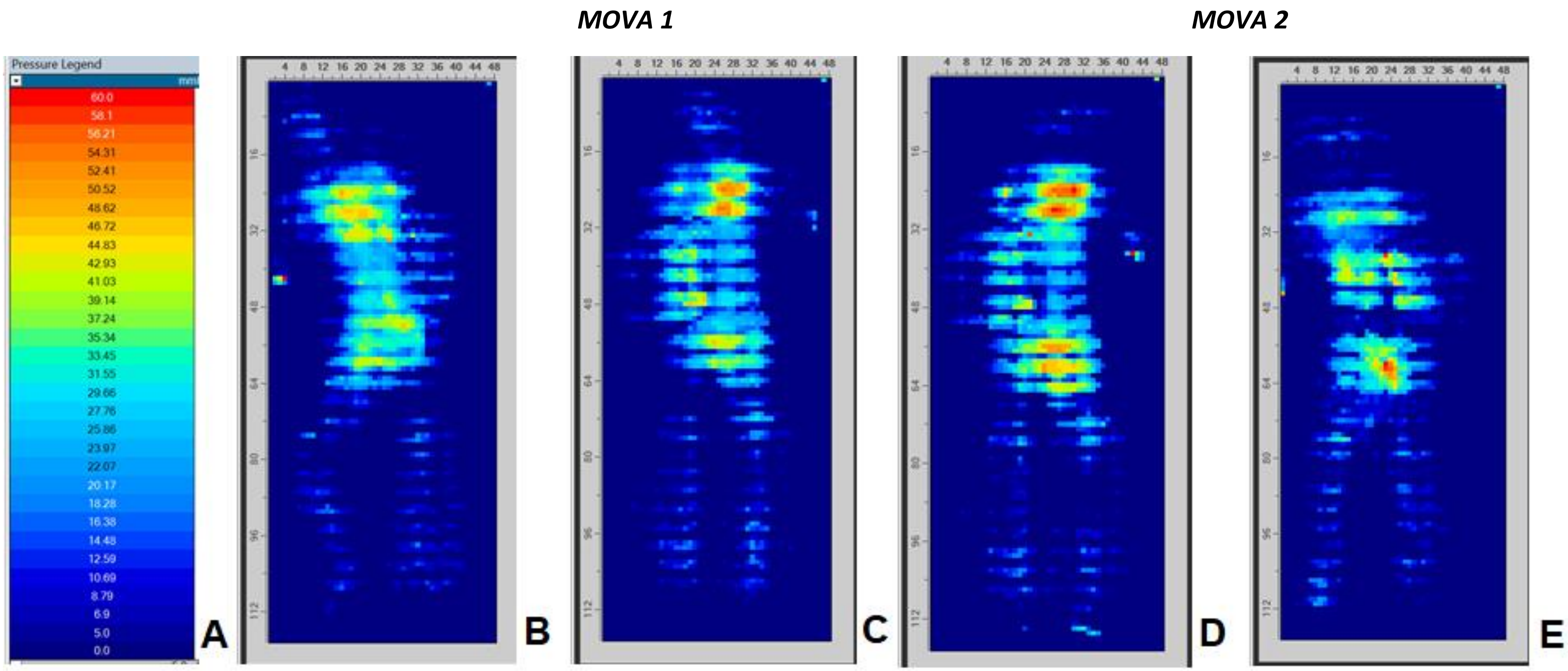


Figure 5.10: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P9 on T1, night 1 of pressure monitoring on the air mattress.



Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
02:57	54	4007	45	24
03:32	56	3986	44	24

Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
08:22	66	3762	47	24
09:07	61	3805	50	19

Figure 5.11: (A) Pressure scale, ranging from 0 to 60 mmHg. Pressure distributions and corresponding pressure parameters for (B) Right side lateral (C) Left side lateral during MOVA 1. (D) Left side lateral (E) Right side lateral during MOVA 2. Magnitude of the four pressure parameters are also indicated.

5.2.2.2 Monitiring lying data (night 2)

P9 was monitored for 15 hours and 32 minutes (932 minutes) on night 2. A summary of MOVAs is outlined in Table 5.9. P9 remained in a static position for extended periods, namely, 392 to 516 minutes. He was positioned in both right and left lateral positions. A single MOVA was identified, resulting in changes to the centre of pressure and contact area, as illustrated in Figure 5.12. This MOVA resulted in changes in pressure distribution, detailed in Figure 5.13.

Table 5.9: Summary of movements on night 2 of timepoint 1 for P9, as determined by continuous pressure monitoring on air mattress.

MOVA	***Time since previous MOVA (mins)***	***Time started***	***Duration (mins)***	***Description***
1	392 minutes	02:58	5	Right side lateral> Left side lateral
Transfer off bed	516 minutes	11:40	11	

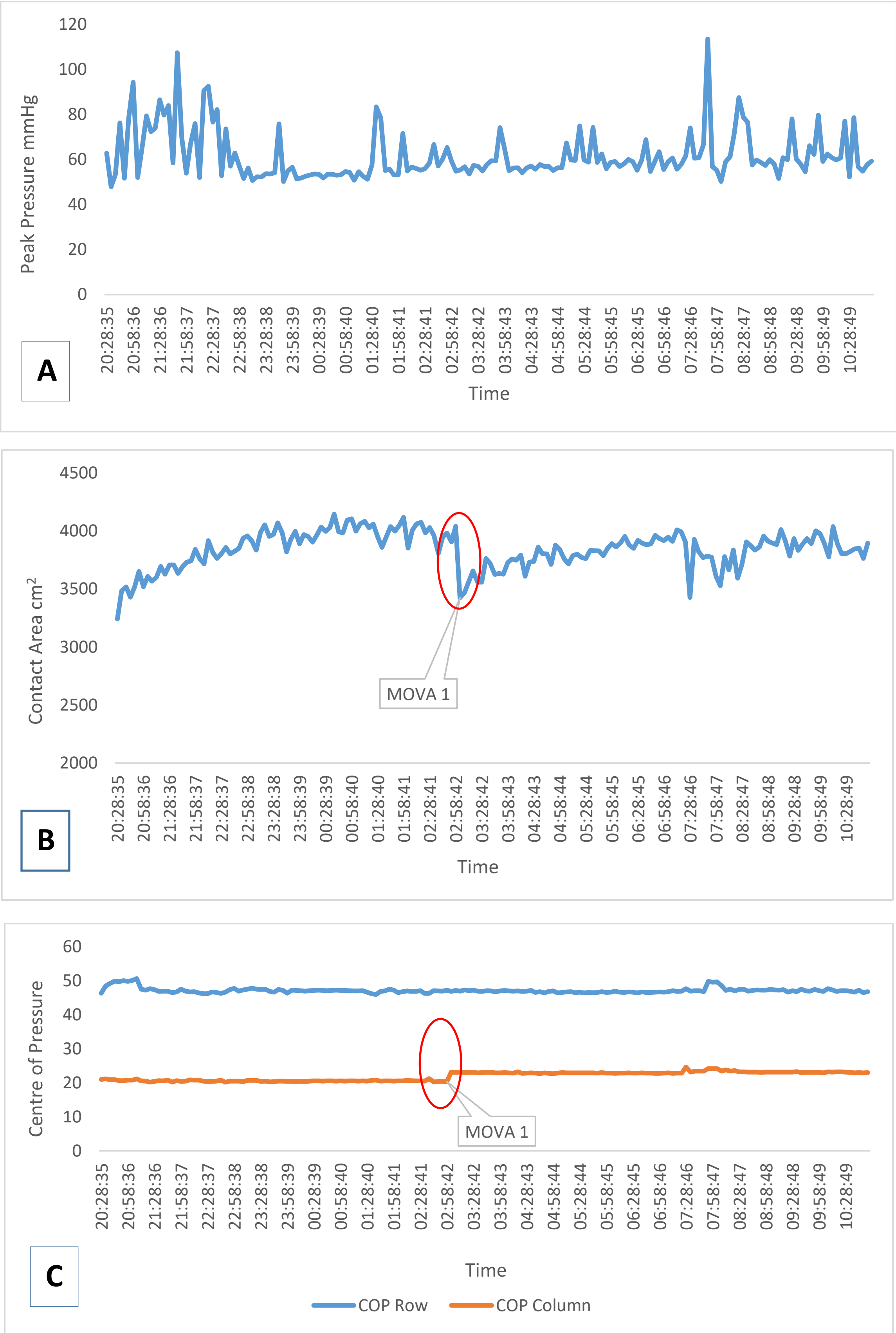
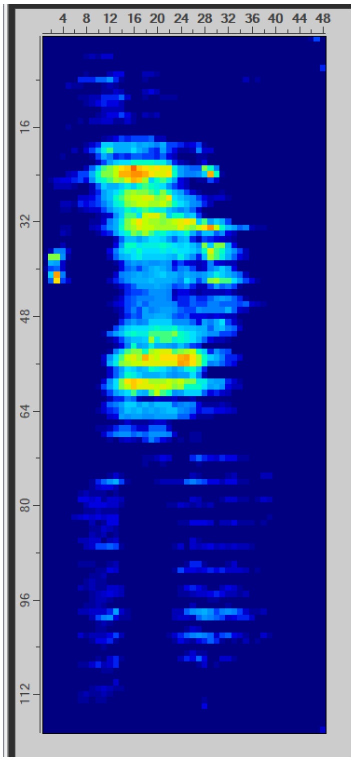
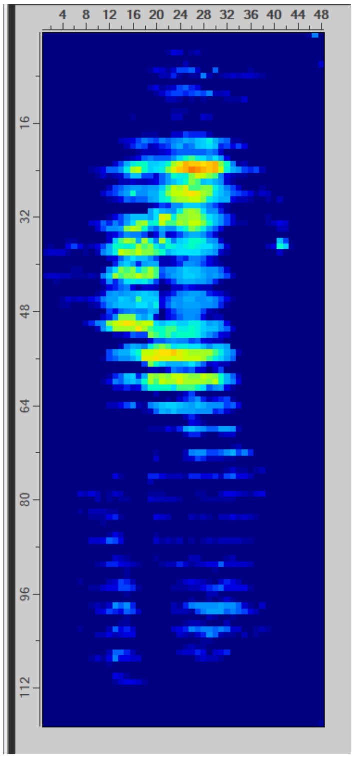


Figure 5.12: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P9 on T1, night 2 of pressure monitoring on a mattress

MOVA 1



A



B

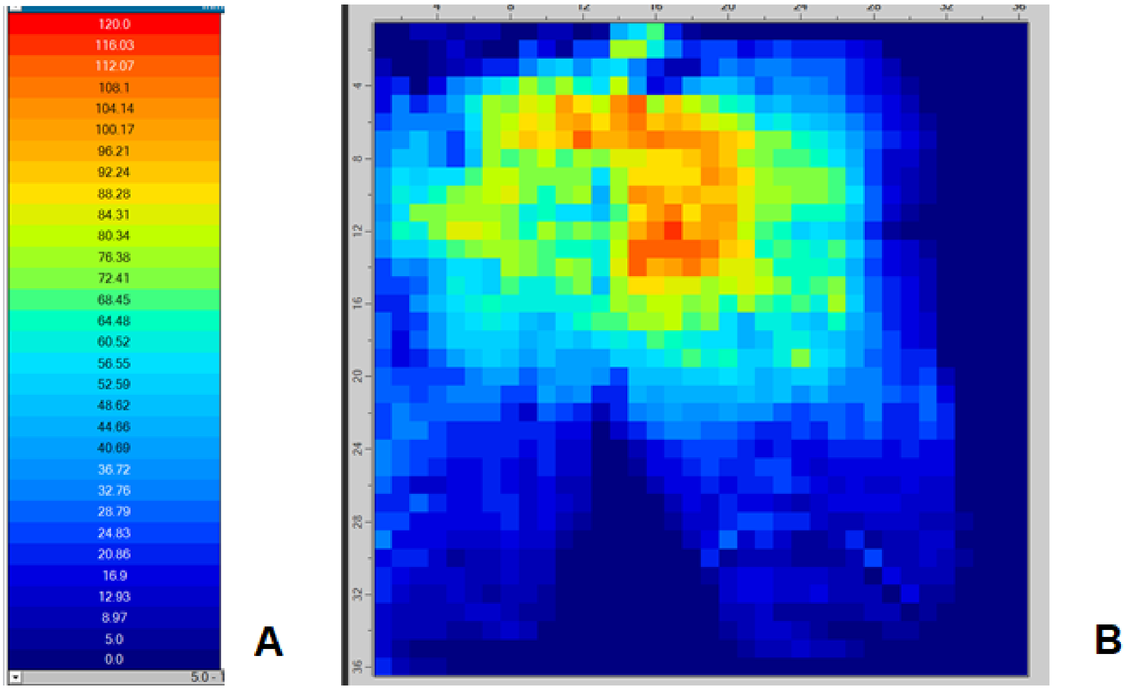
Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
02:58	64	3729	46	22
03:03	55	3760	47	22

Figure 5.13: Pressure distributions and corresponding pressure parameters for (A) Right side lateral (B) Left side lateral during MOVA 1. Magnitude of the four pressure parameters are also indicated.

The pressure profiles from both nights of monitoring reflect the use of an air mattress support system, for which a high degree of immersion was achieved resulting in low peak pressures (55-64mmHg) and high contact areas. The laterally orientated air cells can be visualised in the pressure data, with perturbations in the contact area (Figure 5.12) indicative of an alternating pressure mode in the mattress, periodically shifting pressure values. Similar peak pressure and contact area values were achieved with both right and left lateral tilt positions.

5.2.2.3 Monitoring seating data

P9 was pressure monitored on a wheelchair cushion for two days, for periods of 8 hours 19 minutes (499 minutes) and 8 hours 30 minutes (510 minutes). Figure 5.14 indicates that P9 had a left side pelvic obliquity. It is notable that during day 2 of pressure monitoring on the wheelchair cushion, there were no pressure relieving movements that lasted for longer than 2 minutes.



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
15:49:58	119	1569	13	15

Figure 5.14: (A) Pressure legend ranging from 0-120 mmHg. (B) Pressure distributions in sitting posture of P9. Magnitude of the four pressure parameters are also indicated.

Day 1

P9 had periods of static seated postures for 148 to 206 minutes, with two MOVAs identified as detailed in Table 5.10. These MOVAs were observed in the two pressure-related parameters of COP (Figure 5.15 C and D). However, the movements were less evident in contact area and peak pressure (Figure 5.15 A and B). The two MOVAs are also illustrated in Figures 5.16 and 5.17, with changes in spatial distribution of pressure. It is of note, that peak pressure exceeded 100mmHg during each of movements.

Table 5.10: Summary of movement behaviour of P9 on a wheelchair cushion for two days at time point 1.

MOVA	**Time started**	**Duration *(mins)***	**Description**
1	14:41	24	Lean left and right
2	18:31	8	Forward lean and reposition
Transfer off seat	20:16		

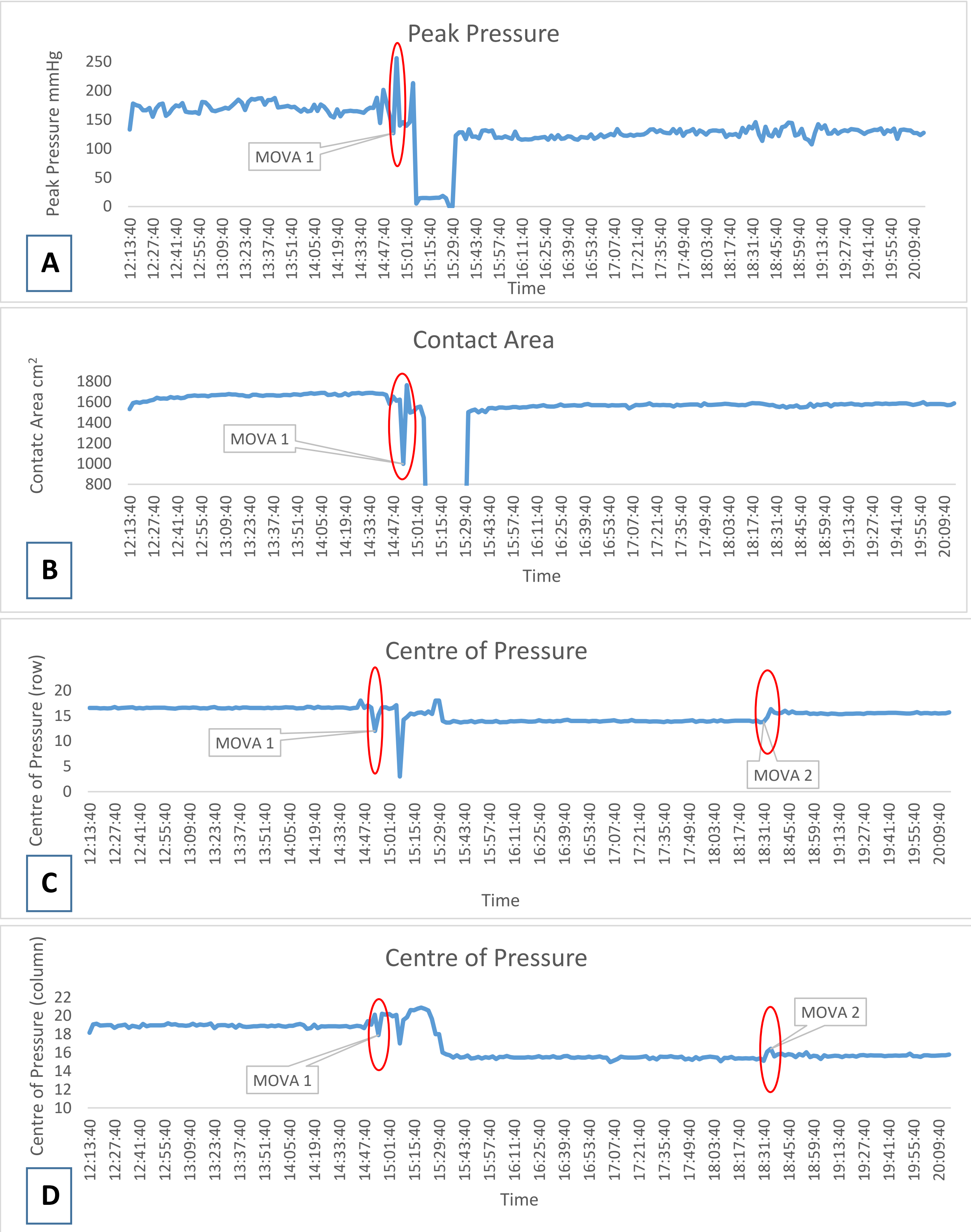
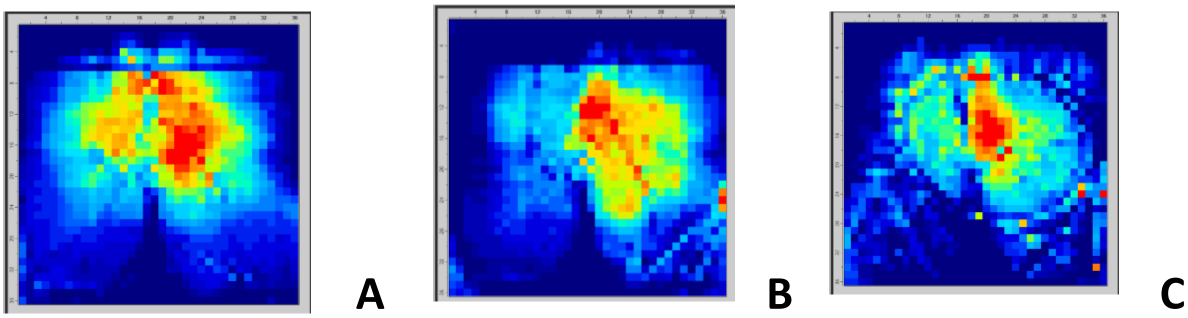


Figure 5.15: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of pressure, column for P9 on T1, day 1 of pressure monitoring on a wheelchair cushion.

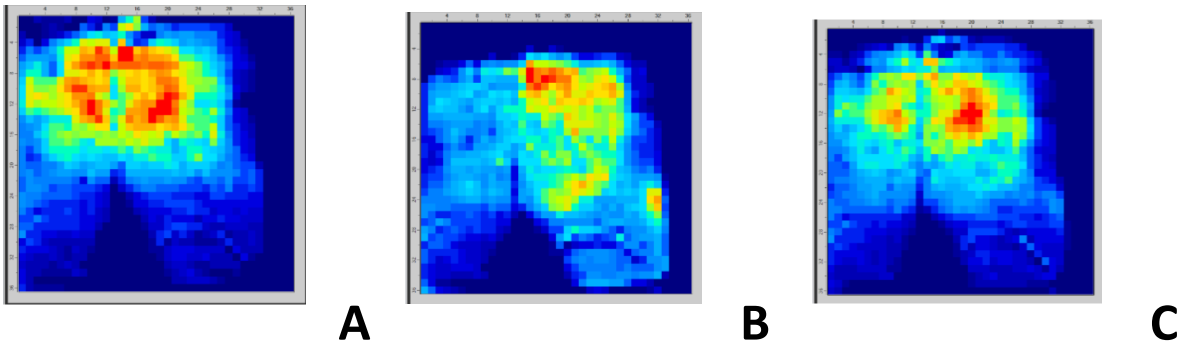
MOVA 1



Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
14:41	170	1682	16	18
14:47	157	1441	17	22
15:05	212	1441	17	20

Figure 5.16: Pressure distributions and corresponding pressure parameters at (A) 14:41 (B) 14:47 and (C) 15:05 during MOVA 1. Magnitude of the four pressure parameters are also indicated.

MOVA 2



Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
18:31	134	1558	13	15
18:34	150	1483	17	17
18:39	137	1559	15	15

Figure 5.17: Pressure distributions and corresponding pressure parameters at (A) 18:31 (B) 18:34 and (C) 18:39 during MOVA 2. Magnitude of the four pressure parameters are also indicated.

Interview

Question: What are P9's current pressure ulcer prevention methods and if there was anything he particuarly liked about them?.

"*I only turn once in the night, erm. But that's because now I've got an air mattress and the seat on the chair has changed completely so."*

It appears he felt that the new support surfaces were very helpful when it comes to skin health. This suggested that he believed that frequent manual turning was no longer needed when using higher specification support surfaces.

Question: What are some of the advantages to his current pressure ulcer prevention plan?

" *Erm I don't know if it's, everybody's more aware of my skin, um since I've had me air mattress, and me new seat and me chair. Everybody, and I mean everybody, puts to bed and gets me up, checks my skin, religiously. So to me, that's brilliant. Cause before they were a little bit, not so much looking at it"*

This indicates that he observed a change in the behaviour of staff after the air mattress was installed. It implies that the staff were more vigilant with skin checking when the participants had been given a higher specification support surface.

Question: Who supports you in carrying out pressure ulcer prevention methods?

"Err yeah like I said, nearly all the staff are, yeah their ever so good. They, because they've sort of been with me all the way through from the bad skin to now and the good skin. Like I said their quite pro-active on it as-well .They are really good".

This indicates he perceived the staff were pro-active in their care.

Question: Was there anybody who did not particularly support P9 in carrying out pressure ulcer prevention?

"*Hmm if I'm honest, I think the doctors*". He went on to explain "*really even on the doctors round it's not been, part of their, their list of things to ask about."*

This suggests he perceived that medical doctors were not particularly involved with pressure ulcer prevention.

Skin checks

No skin damage was noted during skin checks for this period of monitoring .

5.2.3 Participant 3

P3 was 75 years old at the time of monitoring, which took place in April 2019. He was 5 months post injury at T5 level with an ASIA A. He had an episode of discitis, with no sensation or motor function in the legs and chest, otherwise described as paraplegic. This participant, with a BMI of 28 kg/m^2, required the assistance of nurses for all personal care, including repositioning. He also presented with a number of co-morbidities, including osteoarthritis and mitral regurgitation.

Support surfaces

P3 was pressure monitored on a non-castellated foam mattress (Softform premier spinal). He was transferred to wheelchair via hoist, where he was monitored while sitting on a foam cushion with a fluid insert (Jay Balance). He had a history of moisture associated skin damage (MASD) at the buttocks and natal cleft, resulting in both excoriation and broken skin. Pressure monitoring data were acquired over 4 nights, as indicated in Table 5.11. However, wheelchair monitoring was not possible during this period.

Table 5.11: Summary of movement behaviour for P3 on a castellated foam mattress for four nights at time point 1

Night	**Time monitoring started**	**Monitoring period on mattress *(mins)***	**Number of MOVA**	**Minimum time between MOVAs *(mins)***	**Maximum time since between MOVAs (*mins)***
1	17:05:48	1150	3	100	425
2	16:19:34	1241	5	148	300
3	13:01:00	1440	5	132	335
4	13:01:00	1347	5	140	355

Skin Assessment

A small linear red mark on left buttock was noted when pressure monitoring started, although the skin surface appeared intact. It was reported, however, that this site had broken down upon returning to bed on night 2 of the monitoring period. As a result, P3 was restricted to bed rest for the remainder of the monitoring period.

5.2.3.1 Monitoring lying data (night 1)

P3 was monitored for 19 hours and 10 minutes (1150 minutes) on night 1. The summary of movements for night 1 involving both postural changes, personal care and transfer is detailed in Table 5.12. It can be noted that P3 movements were highly variable, with static postures ranging from 100 to 425 minutes during the monitoring period. The equivalent pressure distributions during night 1 are illustrated in Figures 5.19 and 5.20.

Table 5.12: Summary of movements on night 1 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	425	00:10	34	Right side lateral> Left side lateral
2	350	06:16	20	Left side lateral> Right side lateral
Personal care	100	08:16	80	Right side lateral> Supine
Transfer off bed	148	12:04		

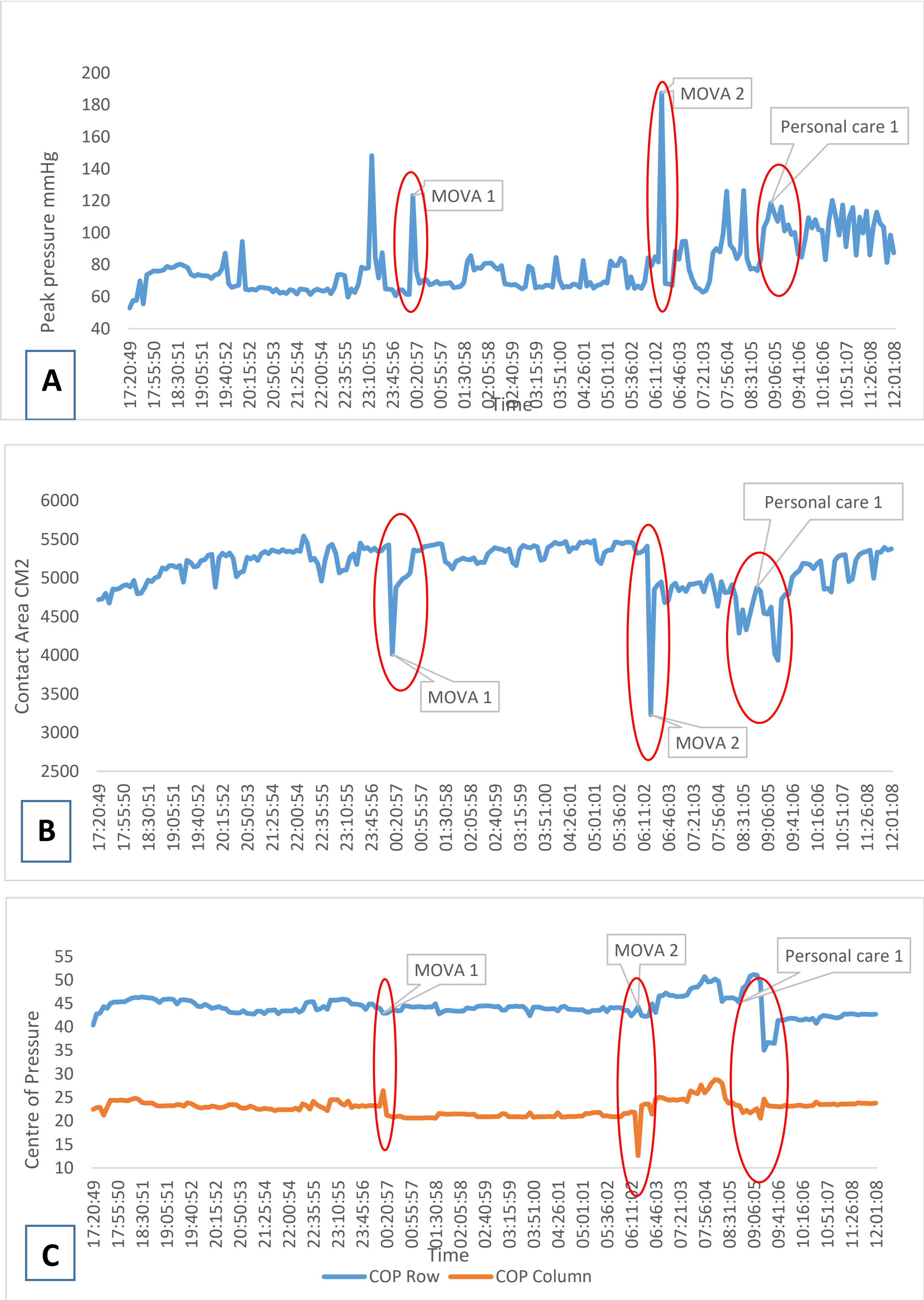
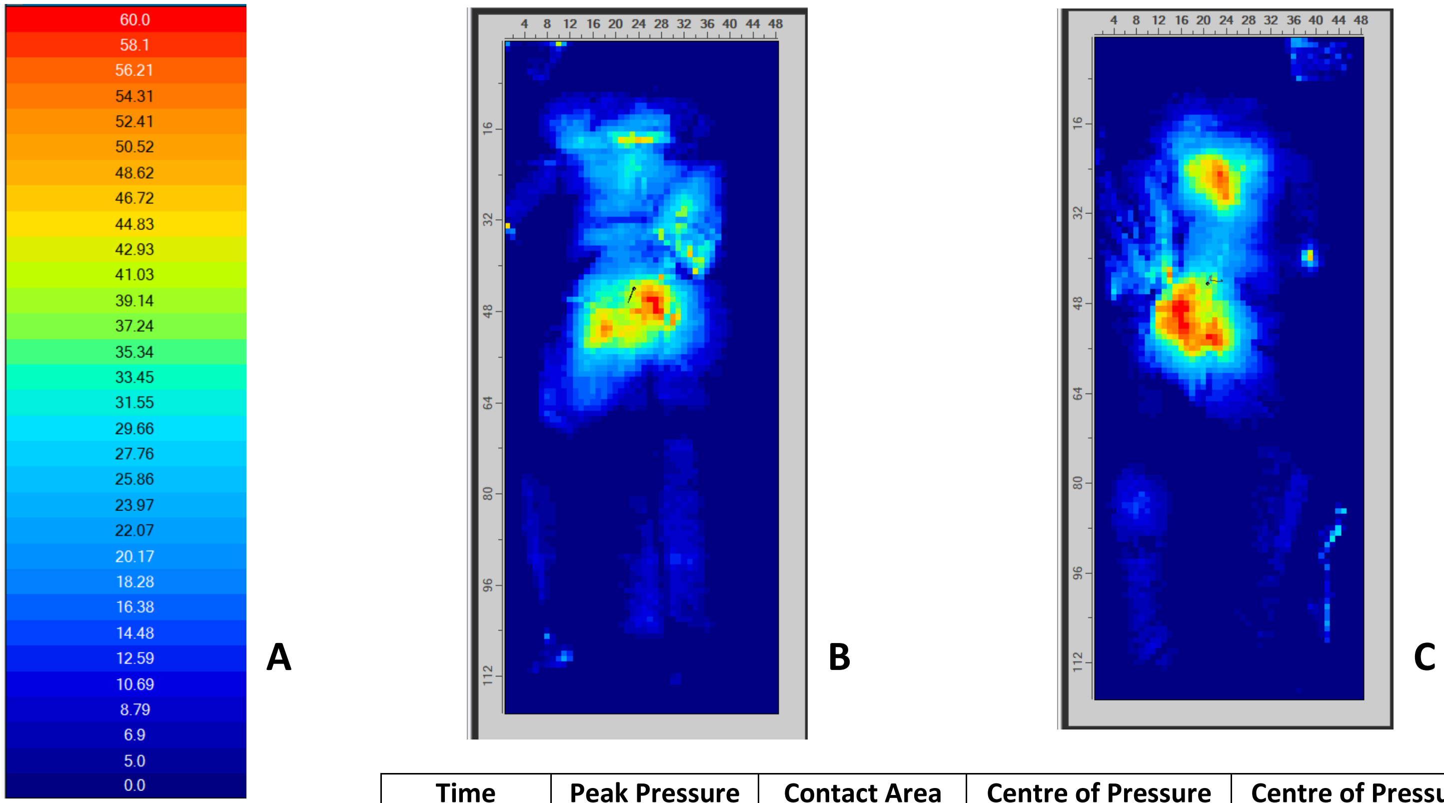


Figure 5.18: Temporal profiles of (A) Temporal profiles (B) Contact Area (C) Centre of Pressure, row, and column, for P3 on night 1 of pressure monitoring on a foam mattress

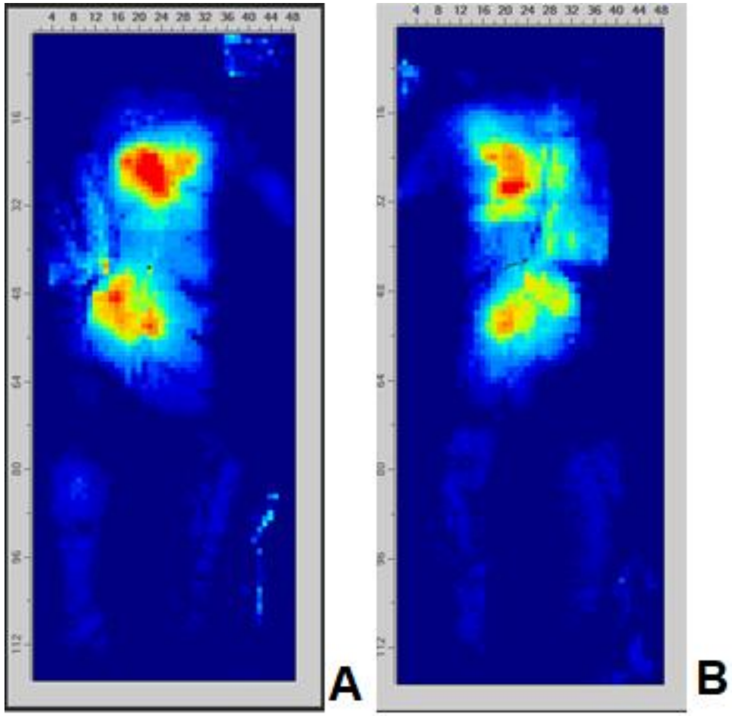
MOVA 1



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
00:10	61	5428	44	23
00:45	68	5362	44	20

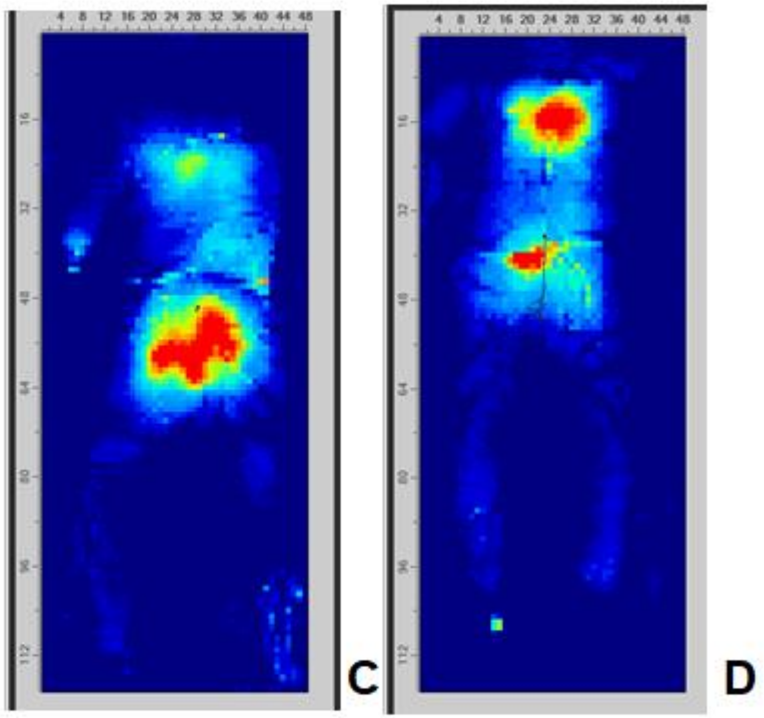
Figure 5.19: (A) Pressure scale from 0 – 60mmHg. Pressure distributions and corresponding pressure for B) Right side lateral (C) left side lateral during MOVA 1. Magnitude of the four pressure parameters are also indicated.

MOVA 2



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
06:16	81	5413	43	21
06:36	67	4949	42	23

Personal care



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
08:16	87	4914	49	28.
09:36	100	4788	36	23

Figure 5.20: Pressure disributions and corresponding pressure parameters for (A) Left side lateral (B) Right side lateral during MOVA 2 and (C) right side lateral (D) during personal care. Magnitude of the four pressure parameters are also indicated.

5.2.3.2 Monitoring lying data (night 2)

P3 was monitored for 20 hours 41 minutes (1241 minutes) on night 2. He was repositioned 5 times during this period, depicted by changes in the four pressure parameters (Figure 5.21). The duration of static postures ranged between 2 hours 20 minutes (135 minutes) to 5 hours (300 minutes). During this period, a linear mark on the left buttock became reddened and the skin was seen to be broken when he went to bed on night 2. Accordingly, he was placed in the running man position by nursing staff. This involved positioning the outside leg, which was not in contact with the mattress, in front of the inside leg. This position ensures pressure is applied to the hip thus ensuring the buttocks/sacrum are off-loaded. The corresponding change in pressure distribution during MOVA 1 is illustrated in Figure 5.22.

Due to the presence of moisture from excoriated skin and sweat, P3 was subjected to a number of washes and bedsheet changes throughout the night. As a result, a single point of personal care could not be identified in this period. It can clearly be seen that both COP Row and Column data deviated significantly during all five MOVAs (Figure 5.21). Sliding sheets were employed more diligently after skin damage was noted. The MOVAs correspond with a decrease in contact area and a change in peak pressure (Figure 5.21). During monitoring, a non-blanching circular red mark was identified on the left hip, corresponding to an area of high pressure values i.e. >100 mmHg (Figures 5.22 to 5.24).

Table 5.13: Summary of movements on night 2 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress.

MOVA	Time since previous MOVA	Time started	Duration	Description
1	148	18:59	30	Right side lateral > Left side running man.
2	265	00:04	30	Left side running man > Right side running man
3	300	05:34	35	Right side running man > Left side running man.
4	135	08:24	30	Left side running man > Left side running man.
5	184	11:58	20	Left side running man > Left side running man.

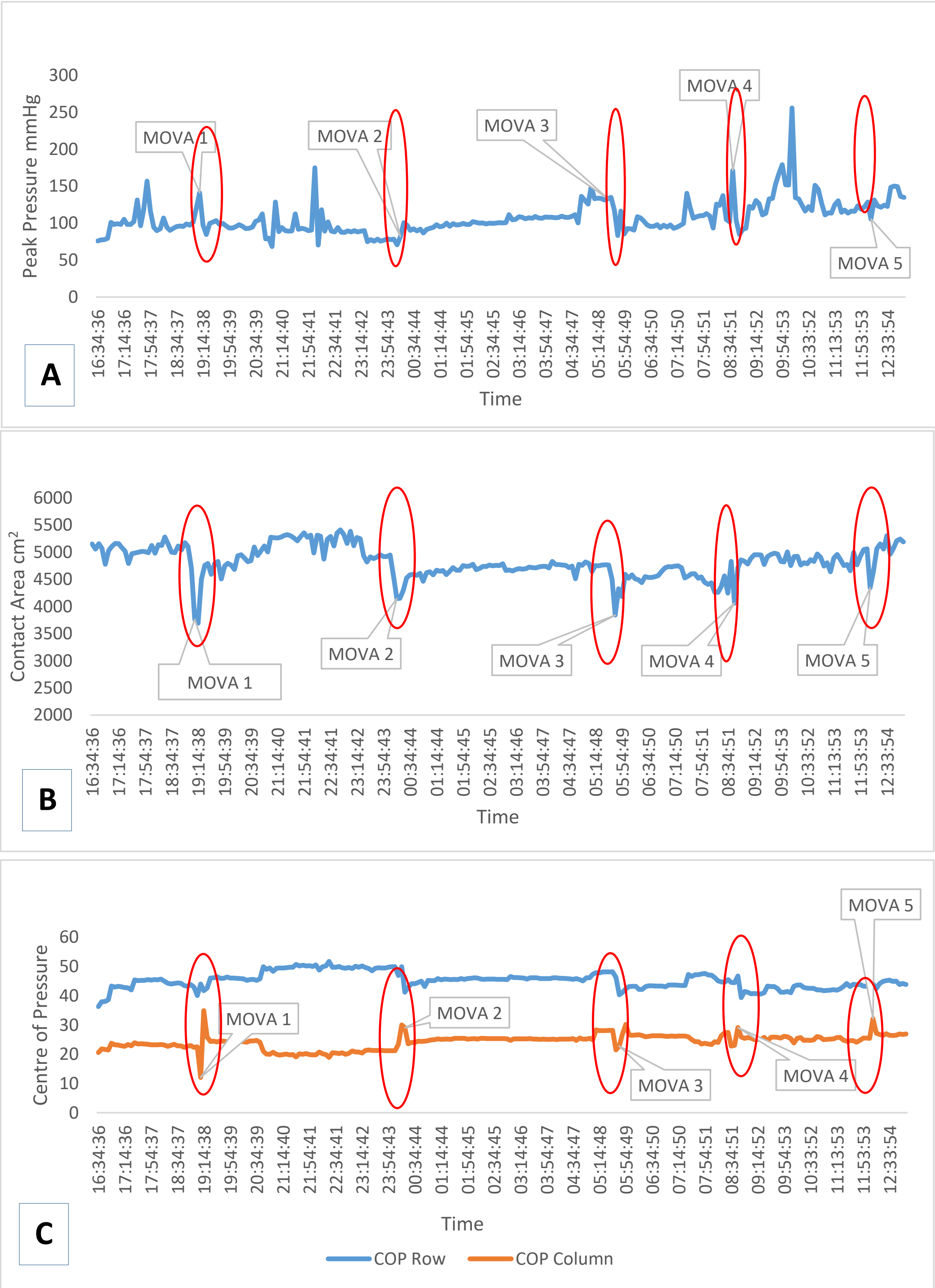
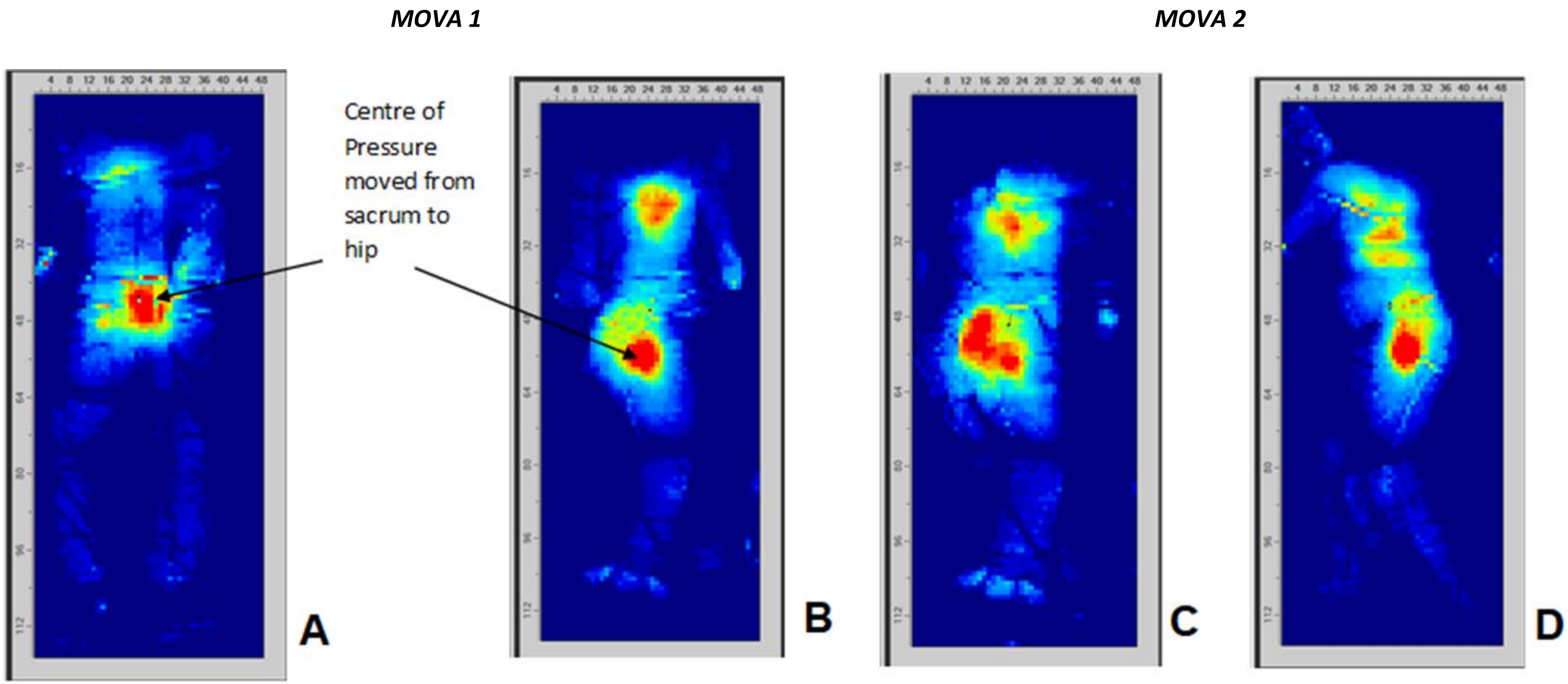


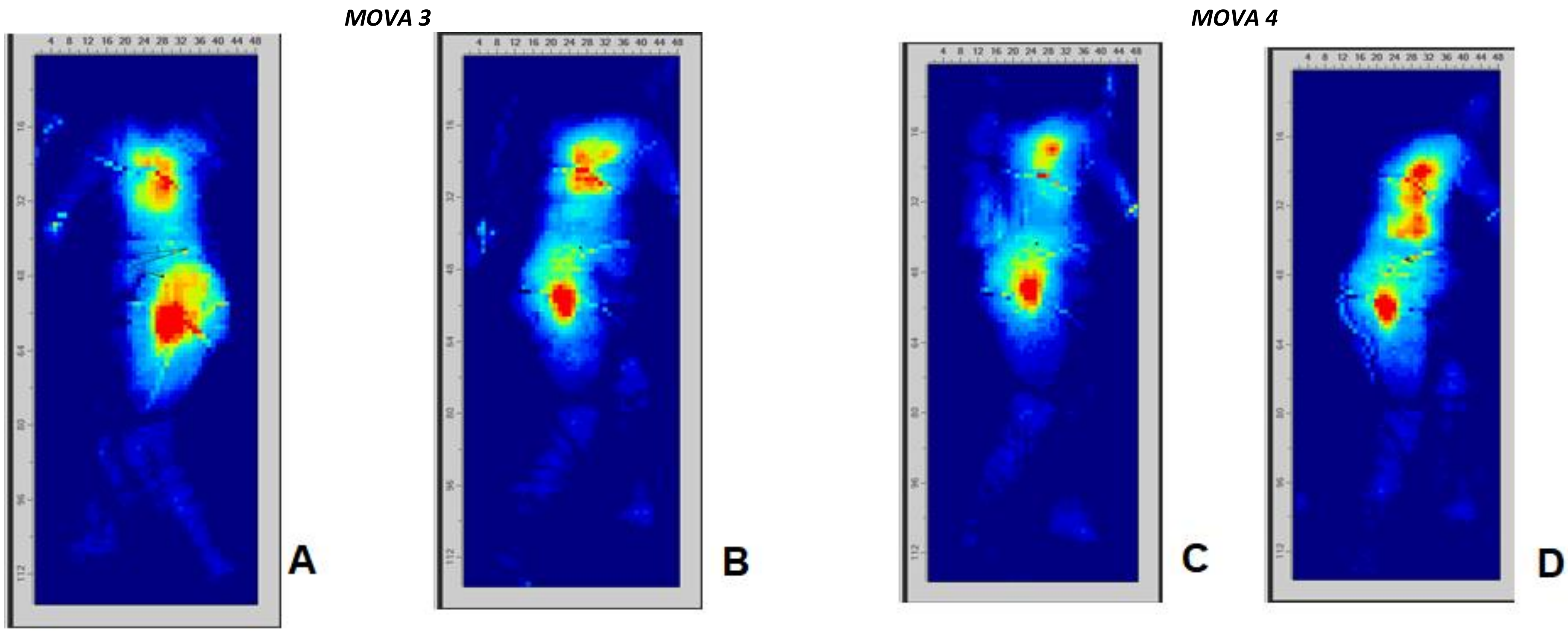
Figure 5.21: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column, for P3 on night 2 of pressure monitoring on a mattress.



Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
18:59	101	5105	42	22
19:29	101	4790	46	24

Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
00:04	**79**	**4924**	**49**	**21**
00:34	**92**	**4581**	**44**	**24**

Figure 5.22: Pressure distributions and correpsonding pressure parameters for (A) Right side lateral (B) left side running man during MOVA 1 and (C) left side running man (D) Right side running during MOVA 2. Magnitude of the four pressure parameters are also indicated.

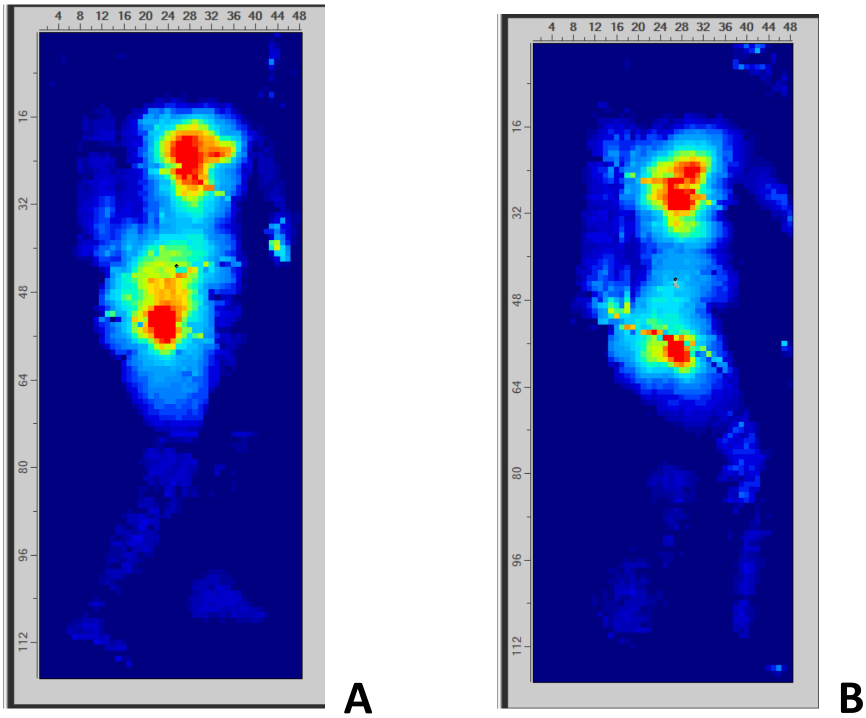


Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
05:34	134	4763	48	28
06:09	90	4584	43	26

Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
08:24	140	4349	44	27
08:54	91	4858	41	25

Figure 5.23: Pressure distributions and corresponding pressure parameters for (A) Right side running man and (B) Left side running man during MOVA 3 (C) Left side running man (D) Left side running man during MOVA 4. Magnitude of the four pressure parameters are also indicated.

MOVA 5



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
11:58	121	5050	43	25
12:18	123	5068	44	26

Figure 5.24: Pressure distribution and corresponding pressure parameters for (A) Left side running man (B) a repositioned left side running man during MOVA 5. Magnitude of the four pressure parameters are also indicated.

5.2.3.3 Monitoring lying data (night 3)

Due to bed rest, P3 was monitored for 24 hrs (1440 minutes) on night 3. He was repositioned 5 times during this period, with temporal changes in pressure related parameters observed in Figure 5.25. His periods of static postures ranged between 1 hour 12 minutes (132 minutes) and 5 hours 35 minutes (335 minutes). As with night 2, he had bedsheet changes and washes during monitoring, so it was not possible to define a single point of personal care. After examining the pressure monitoring, the attendant nursing staff made a decision to move P3 out of the running man position, as it was resulting in tissue damage over the hip. Accordingly, a significant reduction in peak pressures was recorded when the participant was transferred from the running man position to the traditional lateral position (Figures 5.26 to 5.28). This non-blanchable mark disappeared within 12 hours of this change in posture.

Table 5.14 : Summary of movements on night 3 of timepoint 1 for P3, as determined by continuous pressure monitoring on foam mattress

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	132	14:31	15	Right side running man > Left side running man
2	189	17:56	20	Left side running man > Right side running man.
3	300	23:16	35	Right side running man > Left side lateral
4	335	05:26	30	Left side lateral > Right side lateral
5	200	08:26	60	Right side lateral > Left side lateral.

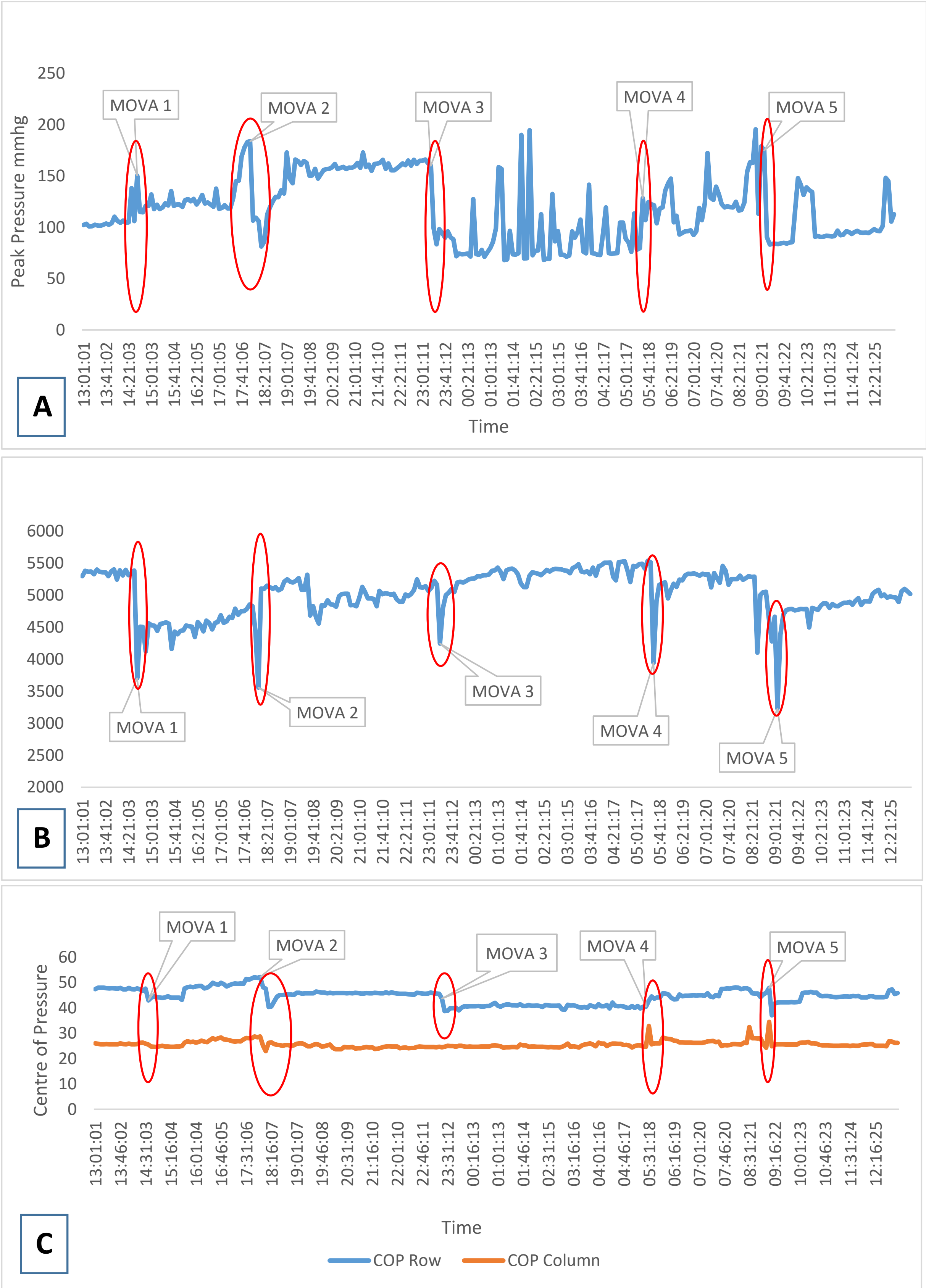
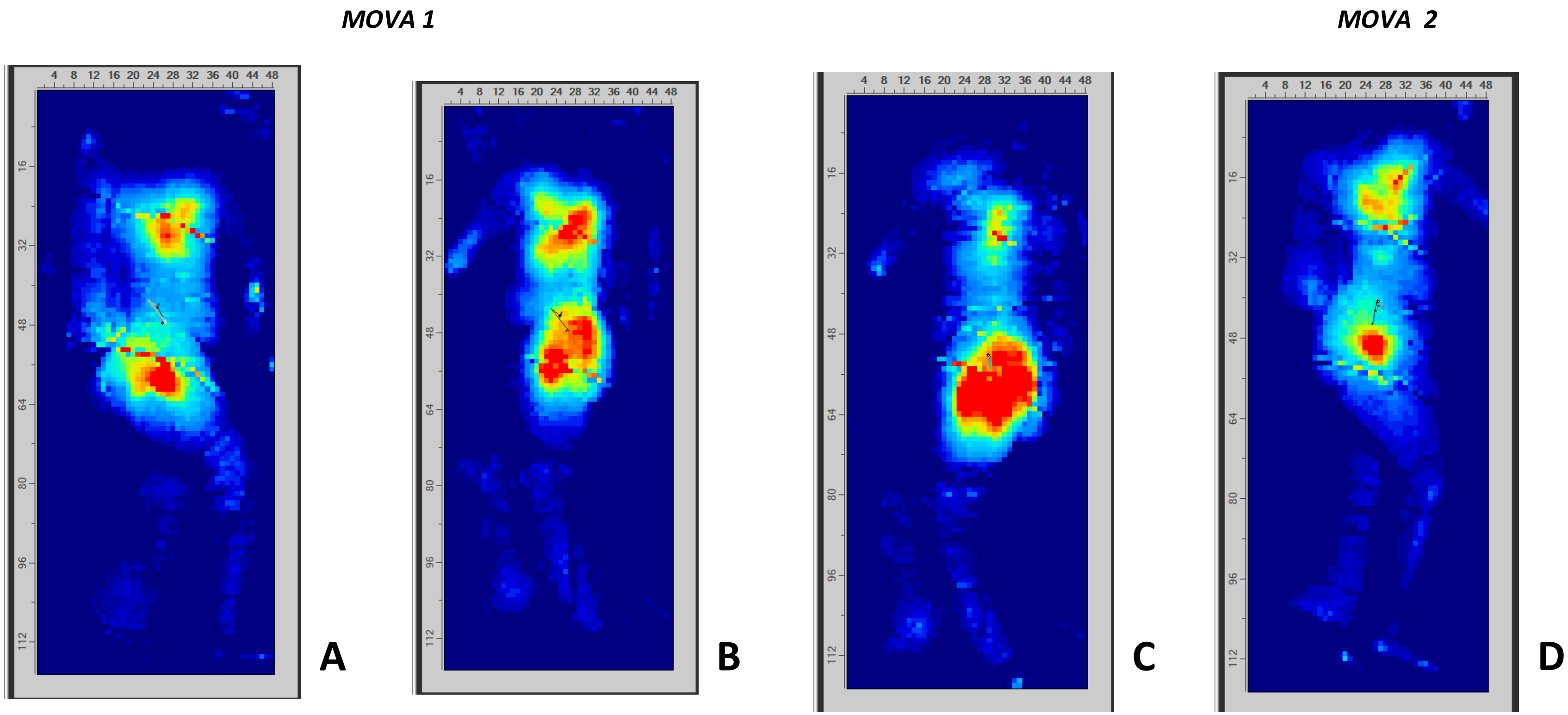


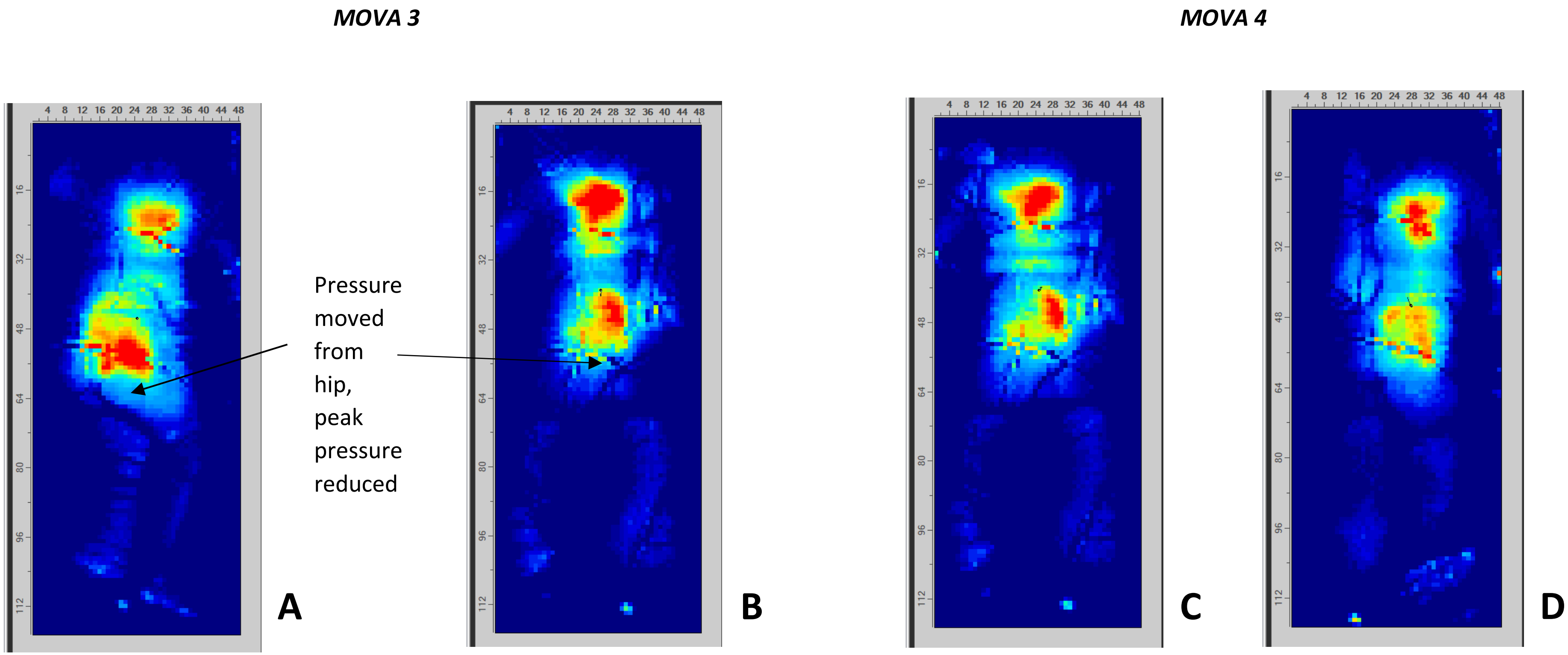
Figure 5.25: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row, and column for P3 on night 3 of pressure monitoring on a mattress.



Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
14:31	106	5383	47	25
14:46	123	4533	44	24

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
17:56	183	4826	52	28
18:16	81	5098	40	26

Figure 5.26 : Pressure distributions and corresponding pressure parameters on (A) Left side running man and (B) Right side running man during MOVA 1 and (C) Right side running man (D) Left side running man during MOVA 2. Magnitude of the four pressure parameters are also indicated.

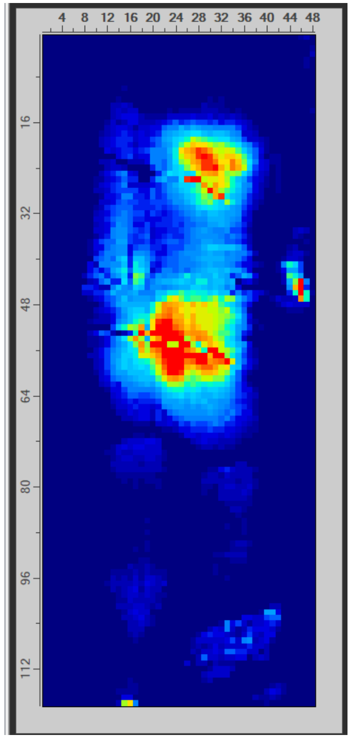


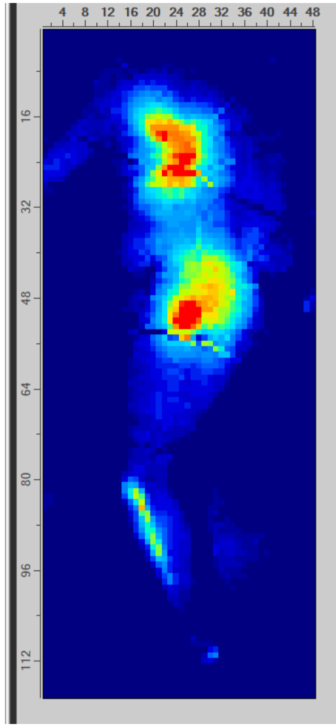
Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
23:16	159	5136	45	24
23:51	90	5196	39	25

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure (Row)	Centre of Pressure (Column)
05:26	79	5514	40	24
06:06	119	5176	45	27

Figure 5.27: Pressure distributions and corresponding pressure parameters for (A) Left side running man (B) Right side lateral during MOVA 3 (C) Right side lateral (D) Left side lateral during MOVA 4. Magnitude of the four pressure parameters are also indicated.

MOVA 5





Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure (Row)	Centre of Pressure (Column)
08:26	117	5287	47	26
09:26	84	4780	42	25

Figure 5.28: Pressure distributions and corresponding pressure parameters for (A) Left side lateral (B) Right side lateral during MOVA 5. Magnitude of the four pressure parameters are also indicated.

Interview

Question: What are P3's current pressure ulcer prevention methods and was there anything he particularly liked about them?

"Well I again I get a bit fed up getting woken up 2 or 3 times in the night to be rolled, but then if it for me own good, how can you complain about it you see"

P3 indicates being woken throughout the night for repositioning is inconvenient, however understands the rationale behind the activity.

Question: Was there anything else he liked or disliked?

"Well they do check it. Some nurses appear to be more authoritative than others ..on it ..um. They say well it either good bad or indifferent. Um, they keep an eye on me because I've had problems before. And it's not perfect now, but it's not split, which is the important bit"

When talking about positioning with pillow P3 also mentioned *"So I have to make sure that they do all that and get it right, cause some of them are, a bit keener than others to get off'*

It appears P3 observed variability the practices of healthcare staff. This is in terms of both decision making, and quality of care.

Question: Are there any discrepancies in the perceived level of care?

"Yeah that's right, some of them are really conscientious about it and others are not so conscientious. Well that's human nature isn't it. So I had to if I'm half asleep of course, they sort of get away with a lot of things.

P3 continues to discuss the variability in care, and how he learned to ensure he is properly positioned with pillows for pressure relief.

Skin checks

As previously mentioned, a red linear mark on the left buttock was noted pre-monitoring. This was noted as broken skin on night 2 of monitoring. After being placed in the running man position for a prolonged period of time, a red circular mark was noted over the left hip during night 2. When repositioned and placed in the lateral position, this mark disappeared within 12 hours. P3 remained on bed rest for the remainder of the monitoring period.

5.3 Analysis of movement profiles

A comprehensive analysis was performed for all 12 participants in phase 3 or 4 of their inpatient rehabilitation, corresponding to timepoint 1. The resulting data regarding MOVAs during the monitoring sessions in both the bed and the wheelchair were identified, as summarised in Table 5.3. Two parameters, namely, the average number of MOVAs per hour and the maximum time between MOVAs, were estimated for each participant over the continuous pressure monitoring period. In order to aide analysis, spinal level of injury has been grouped into the following categories: Cervical, T6 and above, T7 and below. ASIA has been grouped into categories A,B,C,D.

5.3.1 Classification based on participant characteristics

Given the heterogeneity of the participant cohort, it was important to examine whether either of the movement-based parameters could be related to the intrinsic factors of the individual. For this, two distinct characteristics was considered, namely, the level of spinal injury and the ASIA score, with individual details summarised in Table 5.15. There were no participants with Cauda Equina Syndrome who had been recruited into the present study.

Table 5.15: The level of injury and ASIA category for all participants.

Participant	Level of injury	ASIA
P9	C4	A
P11	C4	B
P13	C5	B
P3	T5	A
P14	C8	B
P1	T6	A
P4	T10	A
P15	T11	A
P10	T11	A
P12	L2	B
P8	T4	D
P5	T11	D

5.3.2 Movements in the lying position

The distribution of the two movement-related parameters estimated from clinical observation of the pressure monitoring data with respect to the ASIA type of the participants is presented in Figures 5.29 and 5.30.

Figure 5.29 shows the maximum intervals between MOVAs with reference to ASIA. The histogram demonstrates distinct differences in distribution between those with ASIA A/B injuries and those with ASIA D injuries. ASIA A (median= 6.2 hours, range 2.7-13.7 hours) and ASIA B (median=6.0 hours, range 14.3-13.9) showed longer intervals than ASIA D (median= 4.5 hours, range 2.1-6.8 hours). This trend is also clear when looking at average number of MOVAs (Figure 5.30). Persons spinal cord injury (PWSCI) with an ASIA A (median = 0.19, range 0.00-0.59) and ASIA B (median=0.20, range 0.12-0.89) demonstrated less frequent movements than those with an ASIA score of D (median=0.37, range 0.22-0.51). Although, it is evident, the highest number of MOVAs is attributed to a participant with an ASIA score of B (0.89).

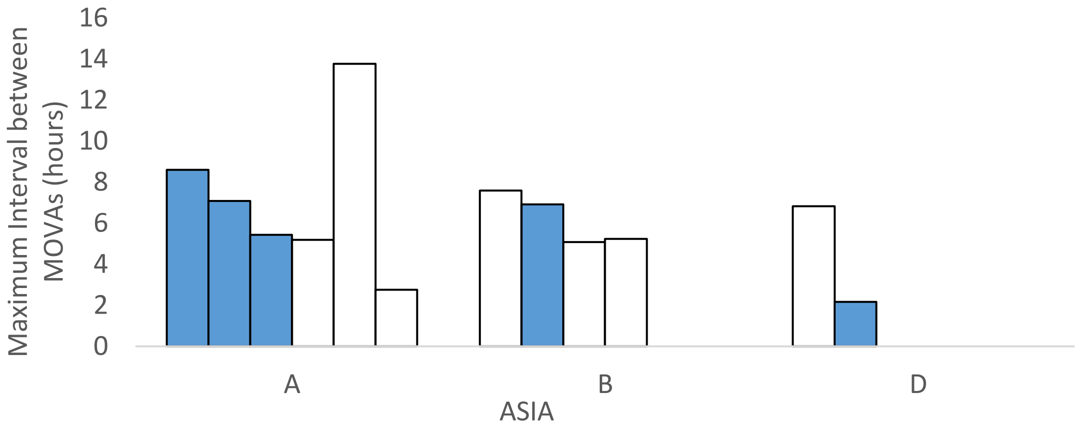


Figure 5.29: Histogram of maximum interval between MOVA in lying position with reference to ASIA - clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

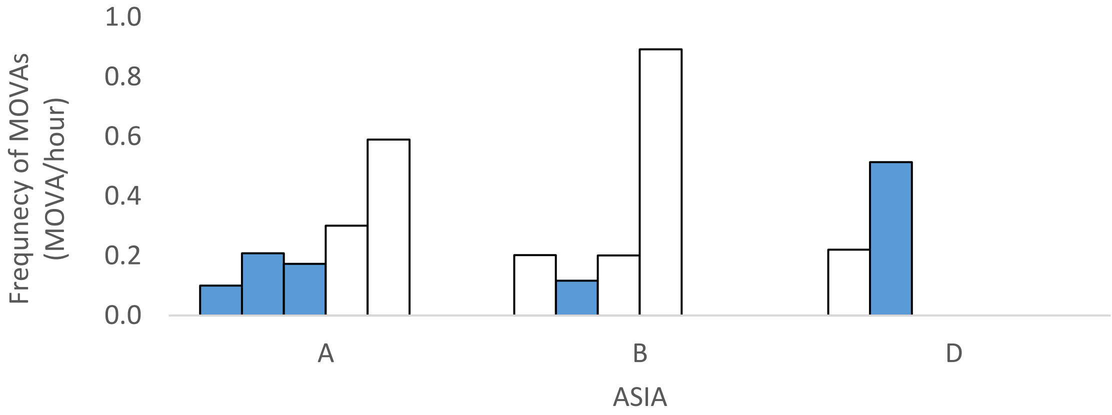


Figure 5.30: Histogram of average number of MOVA in lying position with reference to ASIA - clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

When comparing levels of injury for each participant with the average number of MOVAs per hour, a clear trend is identified (Figure 5.31). As an example, those who present with injuries in the cervical region, demonstrate the lowest number of MOVAs per hour (Median = 0.12, range 0.10-0.20). By contrast, those who present with injuries in the lower thoracic and lumbar spines, demonstrate the highest number of MOVAs per hour (median = 0.41, range 0.00-0.89). It is noticeable that P15, who presented with a low level of injury demonstrated no detectable MOVAs per hour, as this participant lied predominantly on her back. This finding will be discussed later in Section 5.4.

It is evident in Figure 5.32 that those participants with injuries in the cervical spine presented higher maximum times (median = 7.2 hours, range 5.0-8.6 hours) than those with injuries in the lower thoracic and lumber spines (median = 5.18 hours, range 2.7-13.7 hours). One outlier in these results is P15, who demonstrate the longest maximum time between MOVAs, despite a low level of injury. Close examination of the long-term pressure monitoring data suggests that this participant was lying constantly on the back. The visual clinical analysis was thus not able to detect any smaller scales movements associated with this participant.

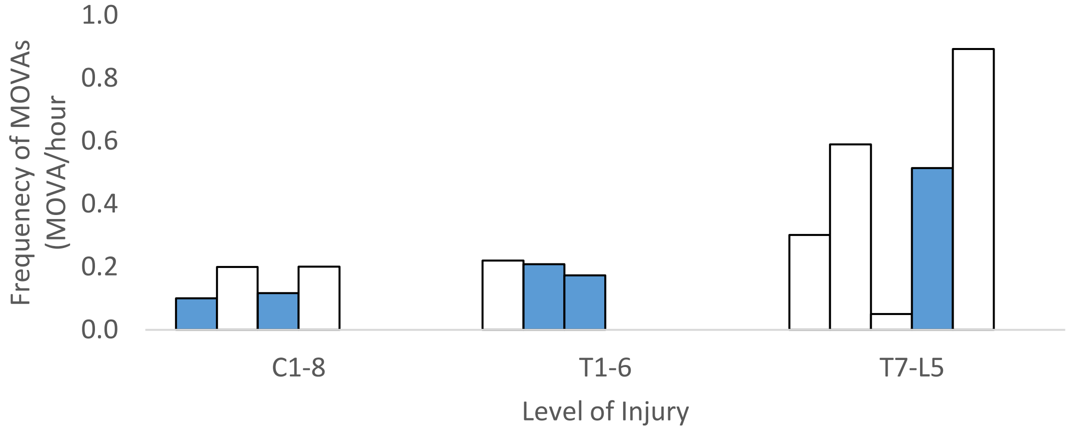


Figure 5.31: Histogram of average number of MOVAs per hour in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

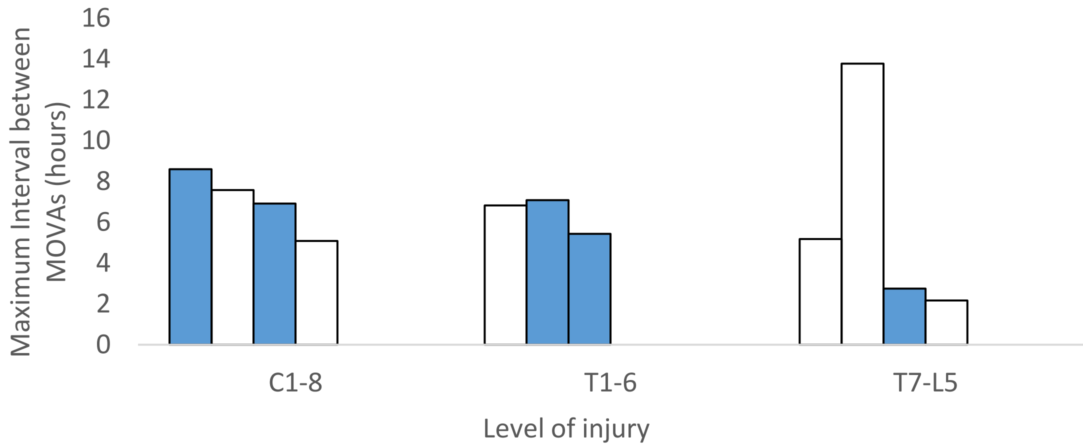


Figure 5.32: Histogram of maximum interval between MOVAs in the lying position with reference to the level of injury of the participants- clinical estimation. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

These overall trends are reinforced when the data is analysed using the algorithm, as demonstrated in figures 5.33 and 5.34. The algorithm is explained in further detail in section 4.8.3. Results produced from the algorithm shows a trend between average number of MOVAs per hour and the level of injury (Figure 5.33). For example, those with injuries in the cervical region presented with lower average of movements per hour (median = 0.71, range 0.39-1.09) than those with injuries in the thoracic and lumber regions (median = 1.82, range 1.16-3.34). This trend is reversed when we investigate the maximum interval between MOVAs (Figure 5.34). PWSCI with injuries in the cervical region had longer times between MOVAs (median=7.8, range 4-10 hours), in comparison to those with injuries in the lower thoracic or lumber region (median=2.7, range 2-4 hours). It also evident that the number of movements detected overall were higher in the algorithm than the clinical observation. Therefore, it may be suggested that the increased sensitivity of the algorithm can provide improved identification of movement patterns and trends.

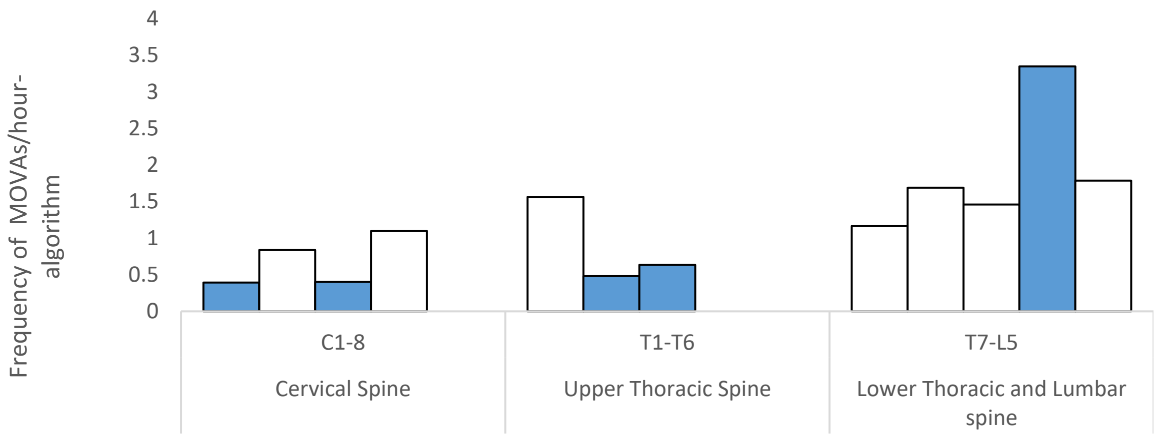


Figure 5.33: The algorithm prediction of average number of MOVAs in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

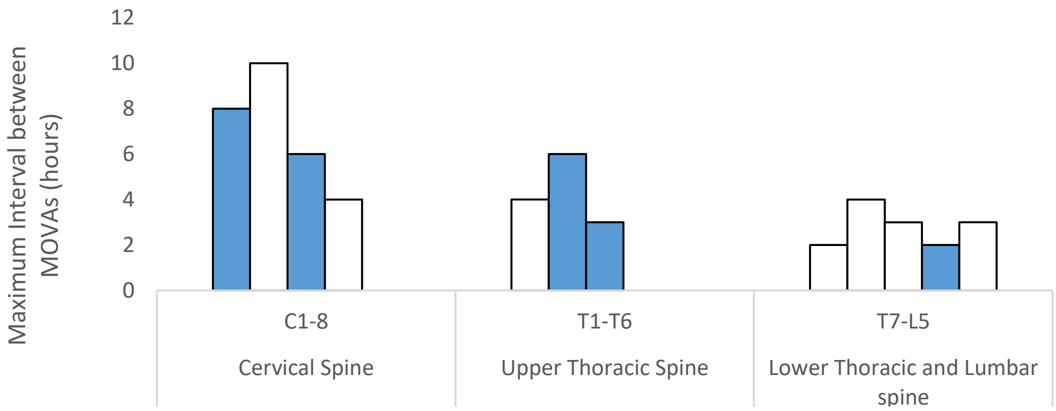


Figure 5.34: The algorithm prediction of the maximum interval between MOVAs in the lying position with reference to the level of injury of the participants. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

5.3.3 Movements in the sitting position

Long term pressure monitoring on the wheelchair cushion presented a challenge when analysing the data to estimate the two movement parameters. As an example, many participants would be transferred off the wheelchair cushion during the day for various reasons, including showering, toileting, or physiotherapy procedures. Although it is probable that these activities generally performed on hard surfaces would create high interface pressure and, as such, not represent periods of pressure relief, accurate predictions of activities out of the wheelchair were not obtained. Therefore, MOVAs identified through the continuous pressure monitoring were only recorded during the hours when the individual was support by their wheelchair cushion.

An estimation of both movement-related parameters with reference to ASIA is presented in Figures 5.35 and 5.36. There were no evident trends for number of MOVAs per hour (Figure 5.35). There is large variability of movement frequency in all ASIA categories. The highest number overall of MOVA is attributed to ASIA B. Interestingly, lowest median is also attributed to be ASIA B, as three out of the four participants with an ASIA score of B moved infrequently (median= 0.00, range 0.00-1.04). There were also no evident trends for maximum times since last MOVA (Figure 5.36). The longest maximum time being attributed to ASIA B (median= 5.0 hours, range 0-7.9 hours).

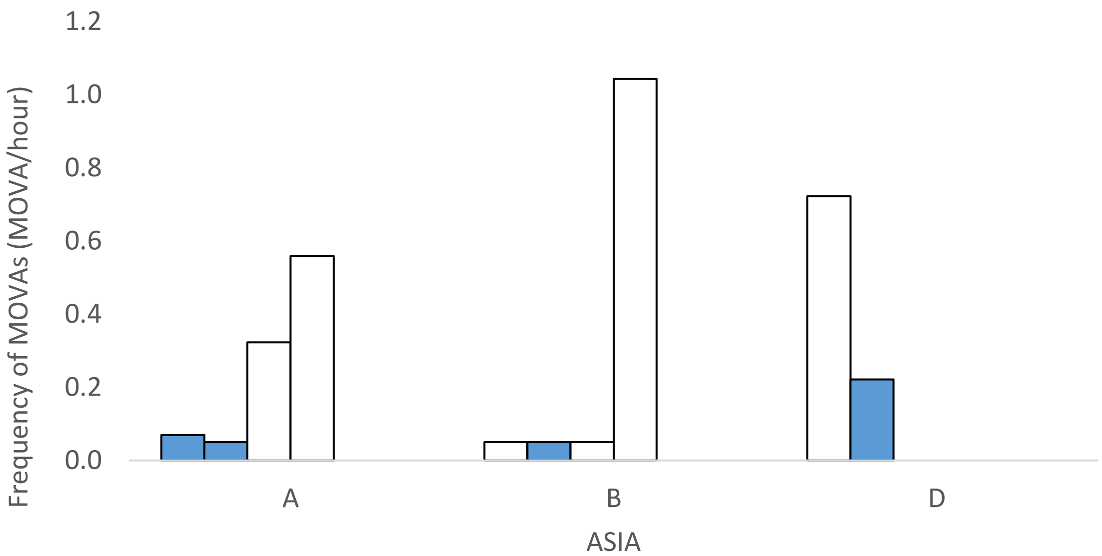


Figure 5.35: Histogram of average number of MOVAs in the sitting position for each ASIA type, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.
Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

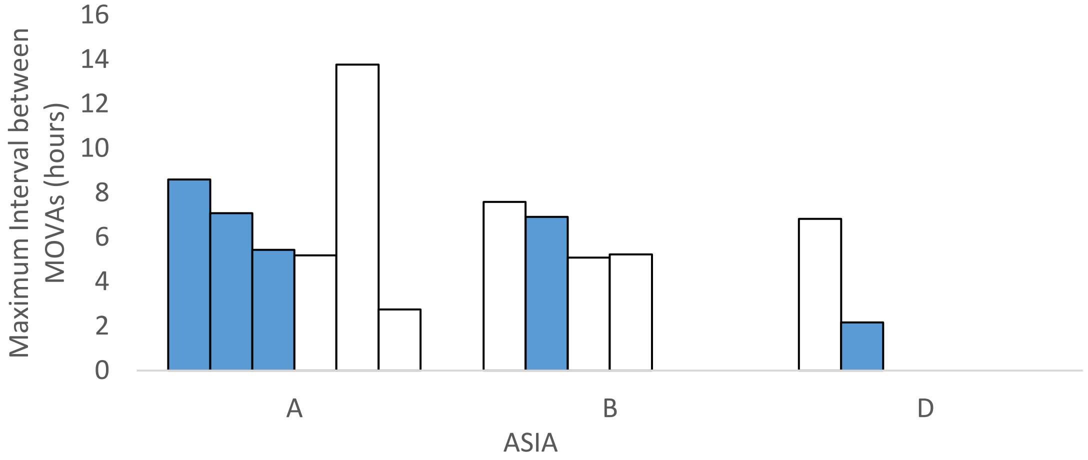


Figure 5.36: Histogram of maximum interval between MOVA in the sitting position for each ASIA type, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

When comparing the level of injury with average number of MOVAs per hour, a significant trend was identified (Figure 5.37). Thus, participants with an injury in the cervical region, have limited movement in the chair (Median = 0.00, range 0.00-0.07), whereas those with injury level in the lower thoracic and lumber regions move more frequently with median value of 0.44 MOVAs per hour (range 0.32-1.04).

With reference to the maximum time between MOVAs in the sitting position, the relationships with the level of spinal injury revealed some trends as shown in Figure 5.38. Those participants with injury level in the cervical region demonstrated prolonged maximum interval between MOVAs (median = 5.1, range 3.0-7.9 hours). By contrast, those with injuries in the lower thoracic and lumber region were static for shorter periods (Median = 2.3, range 0.3-4.6 hours)

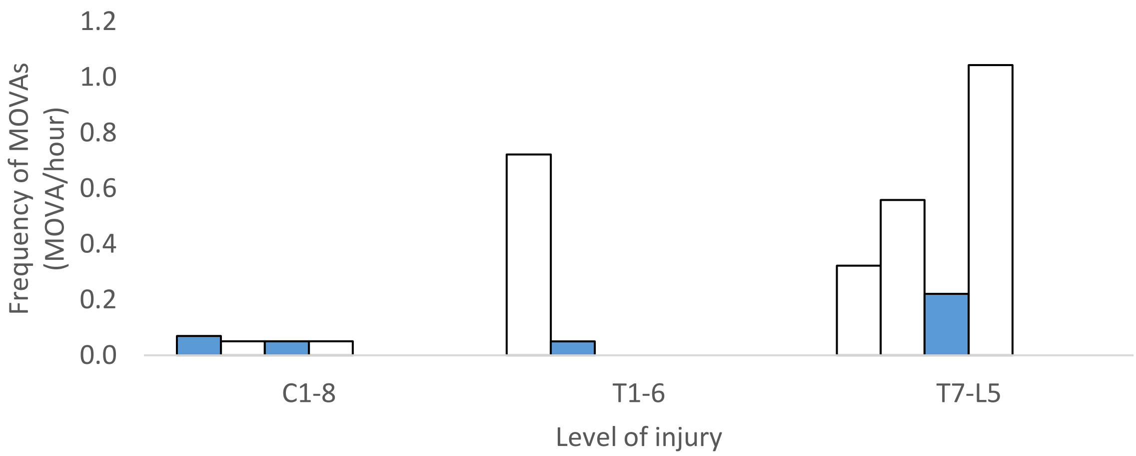


Figure 5.37: Histogram of average number of MOVA in sitting position with reference to spinal level of injury, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

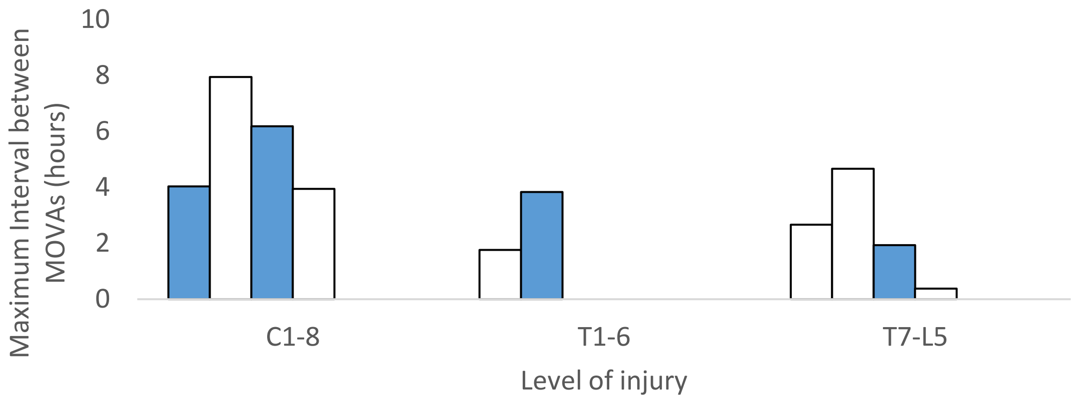


Figure 5.38: Histogram of the maximum interval between MOVAs in sitting position with reference to spinal level of injury, based on clinical estimations. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

5.4 Development of IPUPP

The recommendations proposed in the IPUPP, were developed using 3 types of data

1) Visual analysis of pressure distributions and corresponding pressure parameters.
2) Skin checks
3) Patient preferences expressed in the interview.

Table 5.20 details the recommendations made for each participant. It can be seen they are related predominately to pressure relieving strategies in the wheelchair. No recommendations were made with reference to the mattress type (i.e. foam or air) as the participants appeared to be on an appropriate mattress at this timepoint. No recommendations were made with reference to time in the wheelchair, which was considered appropriate during this timepoint.

Table 5.16: Development of IPUPP

	Aspect of care						
Participant	Wheelchair cushion.	Pressure relieving technique.	Pressure relieving movement intervals	Turning technique whilst in bed	Turn intervals whilst in bed	Posture	Other advice
P1		x	x	x	x		
P3				x	x	x	x
P4	x	x	x			x	x
P5		x	x				x
P8						x	
P9		x	x		x	x	
P10		x	x			x	x
P11		x	x	x	x	x	
P12		x					
P13			x	x			
P14		x	x				x
p15		x	x				x

5.5 Skin damage and pressure/movement profiles

Of particular interest is the pressure profile of participant P3, who formed one of the case studies (section 5.2.3). This participant presented with damage visible on the surface of the skin following periods of sustained high pressures and lack of spatial distribution with localised gradients at the left hip (Figure 5.22).

Other participants who had skin damage which resulted in bed rest were identified in Table 5.2. To examine whether these participants presented with characteristic movement behaviour, the histograms presented above were examined with respect to these individuals who are annotated in a solid blue bar (Figures 5.29-5.38). It is evident that majority of the participants who presented with skin damage had a high level of injury i.e. above T6, an ASIA score of A, and a correspondingly low number of MOVAs. One participant with skin damage i.e. P5, proved the exception. P5 had a relatively low level of injury, an ASIA score of D, and a high number of MOVAs per hour in lying (Figure 5.31). However, it is notable that this participant demonstrated a relatively low number of movements on the wheelchair cushion (Figure 5.37). There were other individuals in the cohort who also presented with low frequency of movement and high intervals between movements, thus precluding generalised statements on the causality of skin damage with respect to posture and mobility.

5.6 Comparison of observed movement vs. predicted movement

To provide consistent clinical analysis of the pressure monitoring data, a method of data reduction and visual verification has been employed. As previously discussed section 4.8.3 an algorithm was also developed.

Both methods of analysis produced similar trends as exemplified when comparing the average number of MOVAs per hour (Figure 5.39). The correlation coefficient between the two methods ($r(10)=0.55$) was statistically significant ($p=0.05$). Close examination of the slope of the linear model i.e. 0.177, however, confirmed that the algorithm predicted higher values for the average number of MOVAs per hour when compared to the corresponding clinical observation. It should be recognised that in addition to large scale movements, the former method detects small scale movements. This is exemplified in the case for P15, who presented with a low level of injury, who was observed clinically to be lying predominantly on her back with no detectable MOVAs. However, the algorithm detected frequent movements of a relatively small magnitude i.e. 1.69 MOVAs per hour for this participant. It is also of note that the higher the number of MOVAs the larger the differentiation between observed and predicted movements, as identified in P12, P10 and P15.

The results of the corresponding analysis with reference to the maximum time between MOVAs is presented in Figure 5.40. In this case, the resulting correlation coefficient was not statistically significant i.e. $p=0.68$, although the findings again revealed that the algorithm predicted a higher number of movements and hence less time between movements. P15 again produced an outlier result from this analysis with a maximum time between MOVAs of only 106 seconds as detected by the algorithm with its sensitivity to small scale movements.

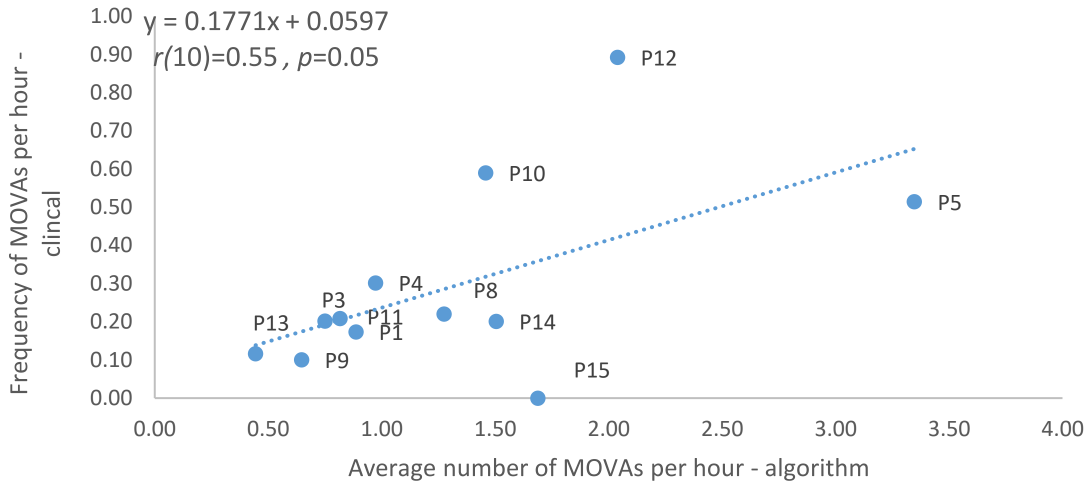


Figure 5.39: The average number of MOVAs per hour as estimated by the clinician compared with those predicted by the algorithm for all the participants during their lying period at timepoint 1.

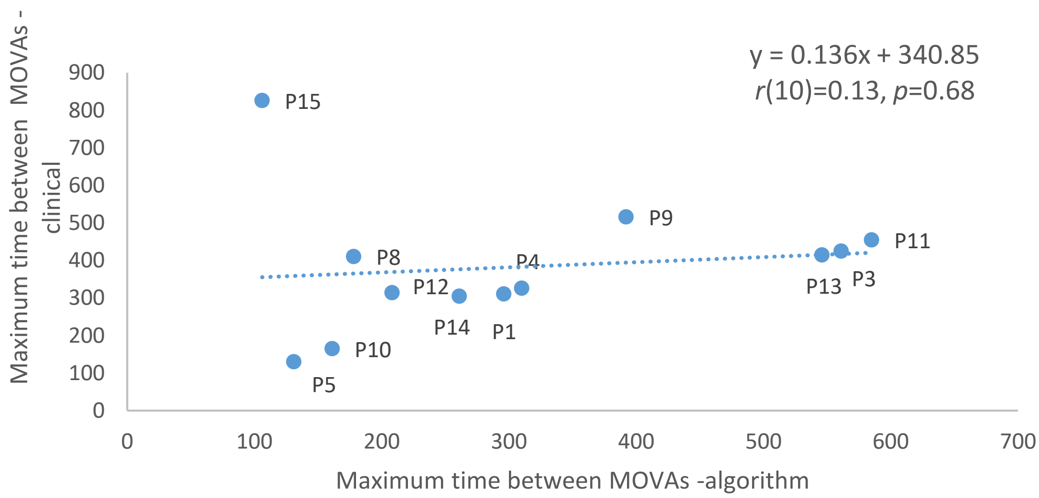


Figure 5.40: The maximum time between MOVAs as estimated by the clinician compared with that predicted by the algorithm for all the participants during their lying period at timepoint 1.

5.7 Discussion

Immobility has been long recognised as an important factor in determining the risk of pressure ulcers in the SCI population. Indeed, their tissue tolerance will be reduced if exposed to mechanical loading for prolonged periods, as described in Chapter 1. Consequently, SCI patients are encouraged to perform regular off-loading of tissues during prolonged periods of sitting or lying to minimise the risk of skin damage. However, a recent study found that self-reporting of pressure-relieving activities in the wheelchair was often inaccurate and, as a result, it is crucial to develop reliable objective means of monitoring such activities (Sprigle et al. 2019).

Although previous literature has investigated movements within the SCI population, the relationship between injury level/severity and movement has yet to be examined (Sonenblum and Sprigle 2018). Therefore, for the first time, this study addresses the temporal movements of SCI individuals while supported on both mattress and wheelchair cushion in conjunction with their ASIA score and level of injury. The initial monitoring at timepoint 1 corresponded to phase 3 or 4 of the rehabilitation for each participant. This data was used to develop a personalised intervention plan (IPUPP), the results from which will be present in Chapter 6.

Case studies were provided for P5 and P9 in this chapter. This was interesting data to present as it represented a low spinal level injury (P5) and a high spinal level injury (P9) from the cohort. It could be seen that movement behaviour was notably different. For example, in the lying position P5 was static for 35-130 minutes (Table 5.4). This was vastly different to P9 who was in a static posture for 115-516 minutes in the lying position (Table 5.7). This indicates a high injury level can result in higher risk of being a static position for an extended period of time. P3, who acquired skin damage whilst undergoing continuous pressure monitoring (CPM) during timepoint 1, was also presented as a case study. When the CPM data was examined, it was evident that a positional change has resulted in high pressures concentrated around the greater trochanters, which subsequently resulted in skin damage (Figure 5.22). This demonstrated the importance of effective distribution of pressure in maintaining skin health. Indeed, our knowledge of aetiology reveals that high pressure values and large gradients of pressure can result in tissue damage in a relatively short period of time (Gefen 2009).

An increase in the average number of MOVAs is evident in those with a lower level of spinal injury. This was observed when positioned on both mattress and wheelchair cushion (Figure 5.31 and 5.37). This trend was reversed when examining the maximum interval between MOVAs. PWSCI with a higher level of spinal injury have increased intervals between MOVA, evident on both the mattress and the wheelchair cushion (Figures 5.32 and 5.38). This is particularly relevant as the prevalence of pressure ulcers has previously been associated with the level of spinal injury (Brienza et al. 2017). These significant trends are highlighted in tables 5.20 and 5.21

Increased intervals between MOVAs was observed in those with ASIA score of A on the mattress (Figure 5.29) Increased average number of MOVAs is evident in PWSCI with an ASIA score of D on the mattress (Figure 5.30). It can be proposed that PWSCI with an ASIA score A are more likely to be in static positions in excess of 6 hours, as they require assistance to perform large scale movements.

Interestingly, these trends are not found when investigating data in the seating position. (Figure 5.35 and 5.36). As shown in table 5.23 the lowest number of MOVA and longest times between MOVA are attributed to those with an ASIA score of B. This is potentially because 3 out of the four participants in the ASIA score of B have injuries in the cervical region. It is plausible this made it challenging to make independent movements in the chair despite the presence of sensation. These

Table 5.17: Summary of median and range values, corresponding to spinal injury characteristic . Notable trends are highlighted in yellow.

		Frequency of MOVAs		Maximum interval between MOVAs	
Spinal Injury Characteristic	Support Surface	Median	Range	Median	Range
ASIA A	Mattress	**0.19**	**0.00-0.17**	**6.2**	**4.3-12.9**
ASIA B	Mattress	**0.20**	**0.12-0.89**	**6.0**	**4.3-13.9**
ASIA D	Mattress	**0.37**	**0.22-0.51**	**4.5**	**3.2-10.0**
Cervical	Mattress	**0.12**	**0.10-0.20**	**7.2**	**5.0-8.6**
T6 and above	Mattress	**0.21**	**0.17-0.22**	**6.8**	**5.4-7.8**
T7 and below	Mattress	**0.41**	**0.00-0.89**	**5.1**	**2.7-13.7**
ASIA A	Wheelchair cushion	0.20	0-0.55	3.2	1.9-4.0
ASIA B	Wheelchair cushion	0.00	0-1.04	5.0	0.3-7.9
ASIA D	Wheelchair cushion	0.47	0.22-0.72	3.2	1.7-4.6
Cervical	Wheelchair cushion	**0.00**	**0.00-0.07**	**5.1**	**3.9-7.9**
T6 and above	Wheelchair cushion	**0.36**	**0.00-0.72**	**2.8**	**1.7-3.8**
T7 and below	Wheelchair cushion	**0.44**	**0.22-1.04**	**2.3**	**0.3-4.6**

When examining the pressure profiles of those participants who presented with skin damage, they predominantly demonstrated low frequency of movements. The exception to this was P5, who had a low level of injury and an ASIA score of D and moved frequently on the mattress. It was of note that this individual had a prolonged static period in the wheelchair. This suggests that PWSCI may have varying levels risks depending on the bed or chair environment. This finding supports a recent study examining the mobility and PU prevalence in older adults which reported that participants demonstrating both high and low movement profiles were at risk of skin damage (Moda Vitoriano Budri et al. 2020). However, it is of note that this study only assessed movements in bed with a piezoelectric load sensor, which could not discriminate between postures and movement types. In addition, the present data collected during the monitoring of P3, has shown directly how sustained high pressures and inadequate spatial distribution of pressure can result in visible skin damage on the surface of the skin. In this individual, for the first time in clinical practice, there appears to be a direct causal link between the measured pressures and the observation of skin damage.

It can also be concluded that the use of the algorithm which interrogates the derivative of the pressure signals can increase the sensitivity in movement detection by identifying both postural changes and postural adjustments to reflect large and small movements, respectively (Caggiari et al. 2021). This machine learning approach provides for an improved identification of temporal patterns and trends in pressure profiles. Indeed, a recent study reported that those PWSCI who performed frequent weight shifts, as opposed to fully off-loading, were less likely to develop PUs Sonenblum and Sprigle (2018). Therefore, the detection of small-scale postural adjustments represent an important characteristic in determining individual risk of developing PUs.

5.8 Summary of key findings

- Increased average number of MOVAs is evident in PWSCI with a lower level of spinal injury, in both bed and wheelchair.
- Increased maximum interval between MOVA is evident in PWSCI with higher level of spinal injury in both bed and wheelchair.
- PWSCI with ASIA scores of A have increased maximum time interval between MOVAs in the lying position
- PWSCI with an ASIA score of D have increased average number of MOVA in the lying position.
- Participants who present with skin damage may demonstrate both high and low frequencies of movement.
- Both clinical and computational analysis using an algorithm produce similar trends. The aforementioned algorithm had increased sensitivity, corresponding to the detection of small scale movements.

Chapter 6 Timepoint 2 results- Analysis of long term pressure monitoring parameters after implementation of individualized pressure ulcer prevention plan

This chapter will evaluate the use of monitoring technologies in the spinal cord injury (SCI) unit following the introduction of the individualized pressure ulcer prevention plan (IPUPP), an example is shown Appendix 1. The original intention was to follow up all 12 participants monitored at timepoint 1, but the intervention of the pandemic and the demand for beds for Covid-19 patients meant that, many of the participants were transferred prematurely from the unit to a community setting. Indeed only 4 participants remained in the SCI unit for follow-up, as summarised in Table 6.1. Ideally, all participants would have been followed up within four weeks of timepoint 1. However, as is often the case with real-world research, this was not always possible, due to COVID-19 restrictions, clinical events, and participant preference- including weekend leave at home.

These were again monitored at timepoint 2 in the hospital setting, using an equivalent protocol to that detailed in chapter 4. Details of their mattresses/cushions and the number of assessments have previously been indicated in Figures 5.2 and 5.3, respectively.

Table 6.1: Participant demographics and co-morbidities timepoint 2

ID	Age	SCI Level	ASIA	BMI kg/m^2	Co-morbidities
P1	64	T6	A	27	Cardiac Surgery
P4	77	T10	A	28	Thoracic AVF and Pulmonary embolism
P9	53	C4	A	27	T2 DM, High cholesterol
P10	74	T11	A	21	Arthritis, high cholesterol and prostate removed

6.1 Timepoint 2 case studies

The results will be presented, as in Chapter 5, in the form of case studies. The primary approach was to examine the temporal profiles in both lying and sitting positions with the estimation of the two selected parameters i.e. average number of movement to offload vulnerable areas (MOVA) per hour and maximum time between MOVAs, as defined in Chapter 4. Both changes between movement behaviour in timepoints 1 and 2 and further descriptors from the data were explored.

6.1.1 Participant 1

P1, who presented with Level T6 ASIA A injury, was monitored for 4 nights and 2 days at timepoint 2, which occurred 6 weeks after the timepoint 1 assessment. Table 6.2 indicates the estimated values for both maximum time between MOVAs and average number of MOVAs per hour, in both lying and sitting positions at both timepoints. It reveals significant improvement in both parameters with respect to sitting behaviour i.e. a decrease in the former and an increase in the latter parameter, respectively. As described in Chapter 5, P1 has use of his arms and hands to assist in pressure relieving activity in his wheelchair, although he often used a table when leaning to provide stability in sitting. In the lying position, however, P1 required nursing assistance to reposition on the mattress. Accordingly, there were minimal differences (~10%) between timepoints in either of the parameters in the lying position (Table 6.1).

Table 6.2: Comparison of movement parameters at timepoints 1 and 2 for P1, as determined by continuous pressure monitoring in both lying position and sitting position.

Measure	***Timepoint 1***	***Timepoint 2***	***Outcome***
Maximum time between MOVAs -lying	**326**	**360**	**No improvement**
Maximum time between MOVAs-sitting	**230**	**141**	**Improvement**
Average number of MOVAs per hour -lying	0.17	0.19	**Improvement**
Average number of MOVAs per hour – sitting	**0**	**0.78**	**Improvement**

Specific recommendations for P1 in the IPUPP included full forward leans at least once every hour during sitting. Table 6.3 details the MOVAs behaviour in the sitting position on day 1 at timepoint 2. Four MOVAs were identified involving forward and side leans, in comparison to timepoint 1 in which P1 recorded no MOVAs. The temporal profiles of each of the four pressure-related parameters in the sitting position are illustrated in Figures 6.1. These reveal a number of distinct peaks and troughs for each of the four parameters. For example for all the MOVAs, there was a decrease in contact area and movement along the COP row, which corresponded to a forward lean and off-loading. There was also a decrease in the peak pressure for MOVAs 1 and 2. By contrast, MOVAs 3 and 4 show movement along the COP column, which represents side leans.

Table 6.3: Summary of movements on day 1 of timepoint 2 for P1, as determined by continuous pressure monitoring on fluid/foam cushion in sitting

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration (*mins)***	**Description**
1	32	12:24:24	4	**Lean forward**
2	32	13:00:24	4	**Lean forward**
3	12	13:16:24	8	**Right side and forward lean**
4	46	14:10:24	6	**Side to side leans**
Transfer off seat	126	16:22:56	-	-

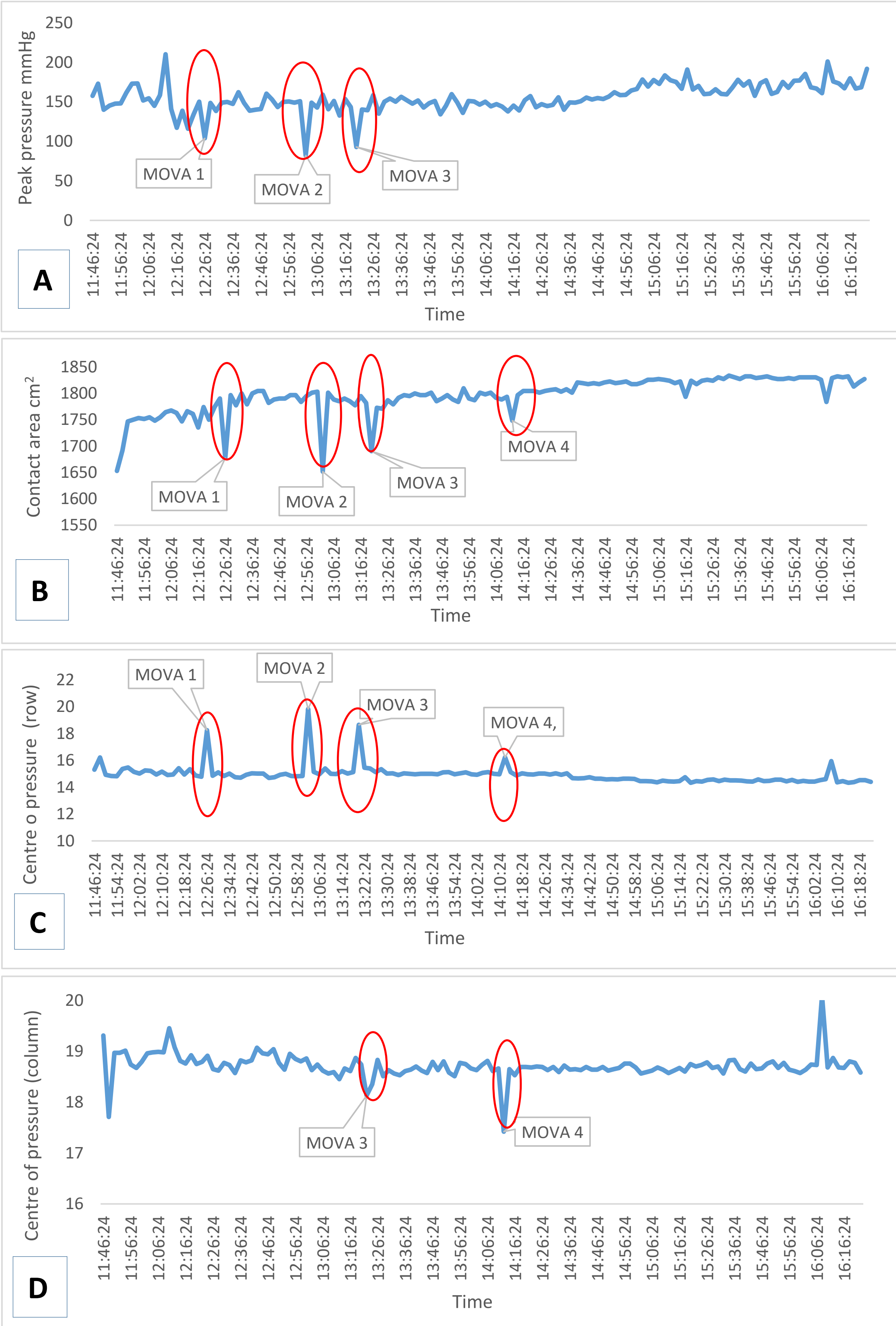


Figure 6.1: Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure row and (D) Centre of pressure column for P1 at timepoint 2, during the first day of pressure monitoring on a fluid-foam cushion while sitting.

P1 had been previously instructed not to lay on his left side, due to previous pressure ulcer (PU) on the left shoulder. Another recommendation was that P1 should not spend more than 3 hours continuously on his back in the lying position during the night. Assessment revealed that P1 followed did not follow this recommendation as summarised in Table 6.4 and in the temporal profiles of the four pressure-related parameters (Figure 6.2). This advice was also not adhered to on each of the other 3 nights of monitoring (data not shown).

Table 6.4: Summary of movements. P1, time point 2, night 1 of pressure monitoring- lying.

MOVA	**Time between MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	300	21:34:01	10	**Right side Lateral> Supine**
2	245	01:49:06	10	**Supine> Right side lateral**
3	249	06:09:10	40	**Right side lateral> Supine**
4	155	09:24:13	25	**Supine> Right side lateral**
Transfer off bed	240	13:49:52		

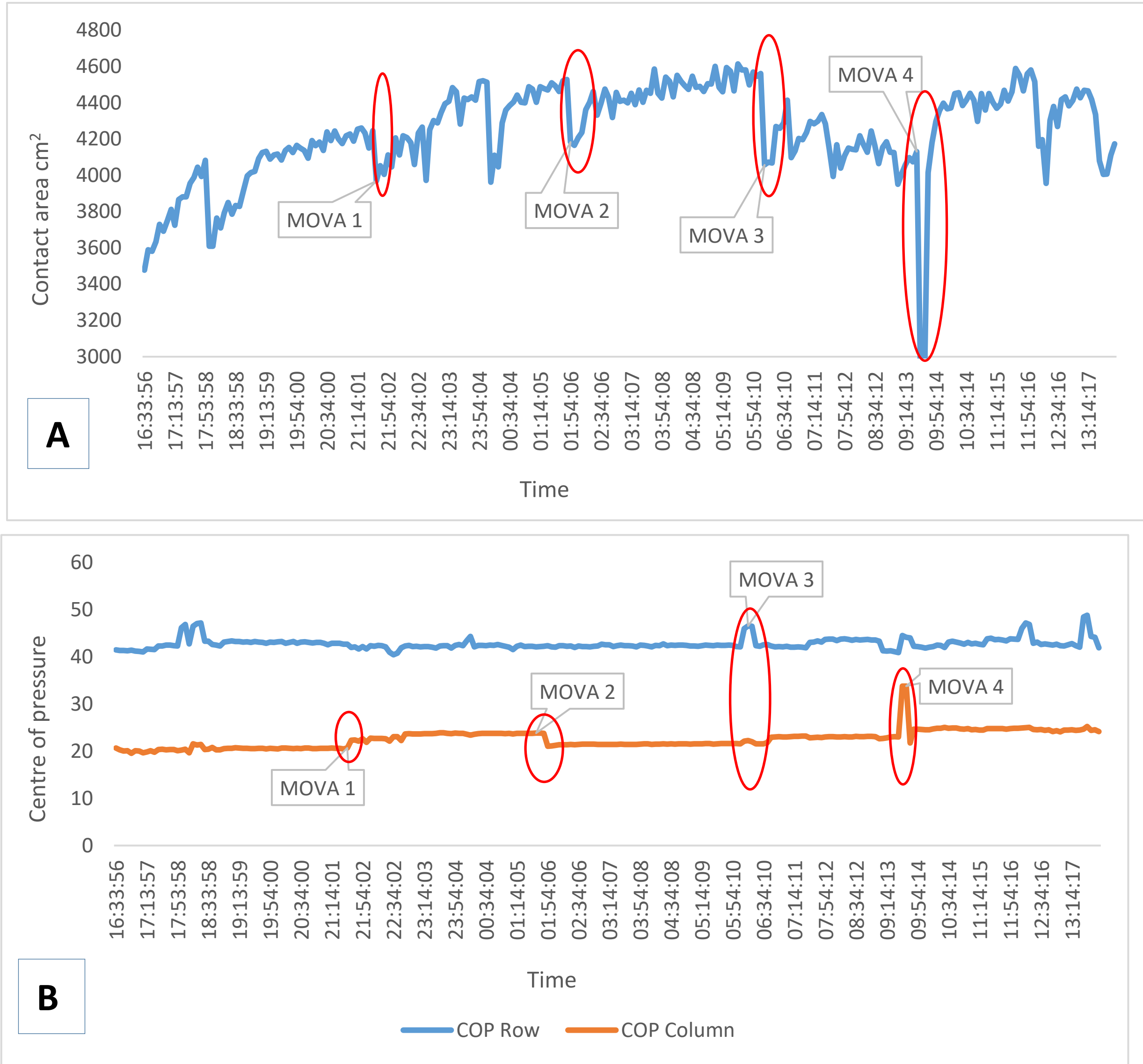


Figure 6.2: Temporal profiles of (A) Contact Area and (B) Centre of Pressure row and column for P1 at timepoint 2, during the first day of pressure monitoring on an air mattress while lying.

Interview with P1

Question: Is there anything you particularly like or dislike about the IPUPP?

"Well just the problem of not being able to always lean forward on something you know its err, that is a bit of problem depending on what you're doing, where you are".

P1 did not express any particular "likes or dislikes" regarding the IPUPP during the interview. However, he did identify some challenges when discussing the forward lean manoeuvres in the sitting position, in particular.

Question: Do you perceive there to be any advantages or disadvantages to the IPUPP?

"*Well anything that can stop marks and blemishes and whatever on the skin is um probably good. Obviously got a long time to go hopefully, before I, you know pass away"*

P1 goes on to say "*bed rest is getting a bit tiresome now"*

P1 showed a good understanding of the advantages of PU prevention, He had also experienced bed rest due to skin problems which appeared to provide some motivation to maintain skin health

6.1.2 Participant 4

P4 was monitored for 2 nights and 2 days at timepoint 2, which occurred 6 weeks after the timepoint 1 assessment. Table 6.5 indicates the estimated values for both maximum time between MOVAs and average number of MOVAs per hour, in both lying and sitting positions at both timepoints 1 and 2. There were clear differences in the findings, with a large increase (166%) in the maximum time between MOVAs in the sitting position and a minimal change in the corresponding parameter in the lying position. The values for the average number of MOVAs per hour for both positions decreased for timepoint 2, which strongly implied a worsening situation. As discussed in Chapter 5, P4 has use of his arms to assist in pressure relieving activities for repositioning in both the bed and the wheelchair.

Table 6.5: Comparison of movements at timepoints 1 and 2 for P4, as determined by continuous pressure monitoring in both lying position and sitting position.

Measure	***Timepoint 1***	***Timepoint 2***	***Outcome***
Maximum time between MOVAs –lying	**311**	**285**	**Improvement**
Maximum time between MOVAs-sitting	160	427	No improvement
Average number of MOVAs per hour -lying	0.30	0.21	No Improvement
Average number of MOVAs per hour - sitting	0.32	0.13	No Improvement

Specific recommendations in the IPUPP designed for P4 included a forward lean of 2-3 minutes every hour. Assessment revealed that P4 did not adhere to these recommendations, as summarised in Table 6.5. It can be seen that the maximum time between MOVAs significantly increased. There was also a small decrease in the average number of MOVAs per hour. Figure 6.3 also indicates a period of 425 minutes in which there were no significant perturbations in the displacement in the COP, indicating an absence of pressure relieving activity. In the lying position, no specific recommendations were made in the IPUPP for P4 in terms of frequency of repositioning.

Table 6.6: Summary of movements on day 1 of timepoint 2 for P4, as determined by continuous pressure monitoring of foam cushion in sitting.

MOVA	**Time between MOVAs *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	36	11:05:29	4	**Forward lean**
Transfer off seat	427	18:16:55	-	**-**

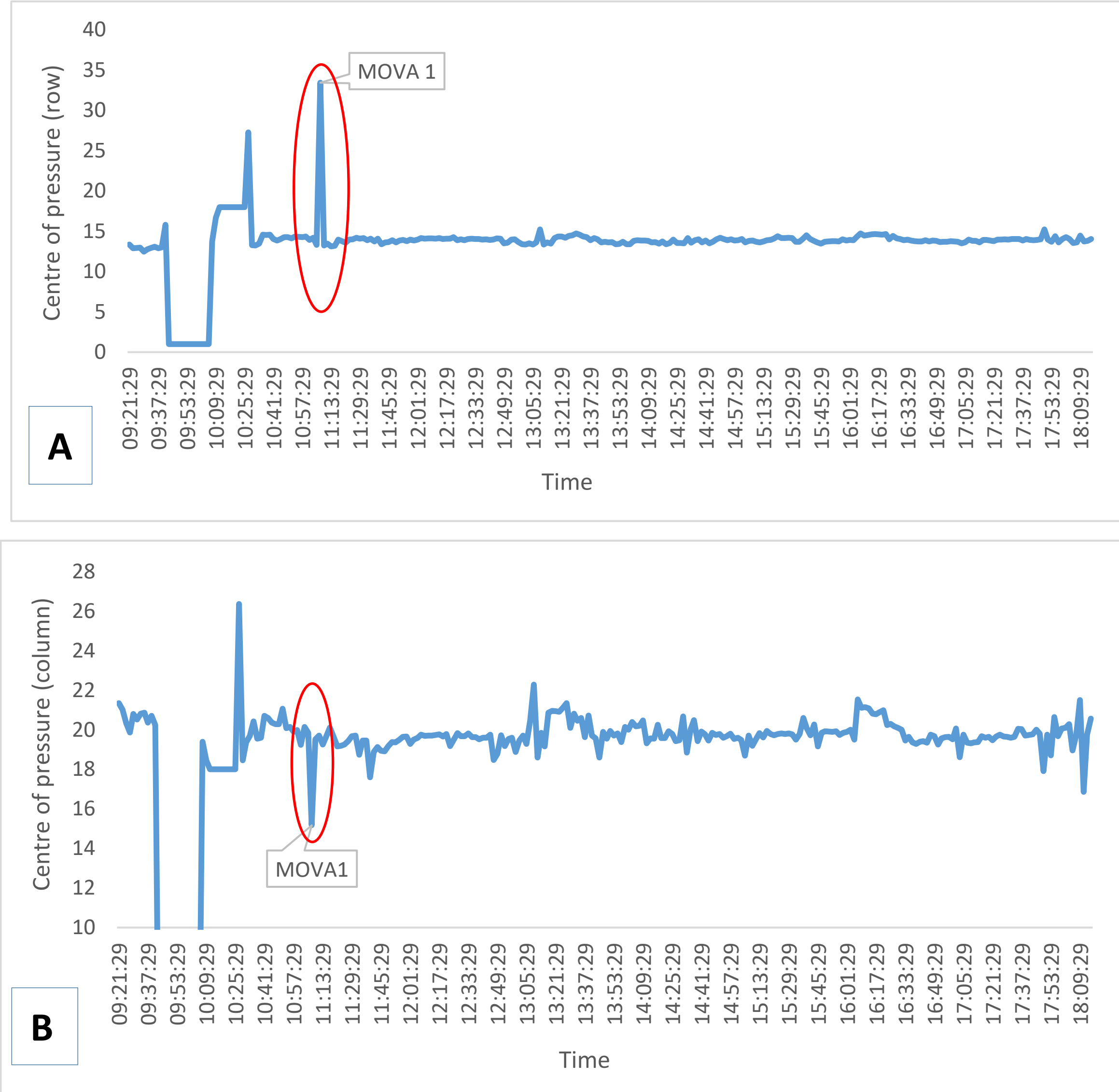


Figure 6.3: Temporal profiles of (A) Centre of Pressure row and (B) Centre of pressure -column for P4 at timepoint 2, during the first day of pressure monitoring on a foam cushion while sitting.

Interview

Question: Do you perceive there to be any advantages or disadvantages to the IPUPP?

" I wasn't aware of any disadvantages or advantages really".

P4 did not have any particular likes or dislikes when it came to the IPUPP. He also did not identify any advantages or disadvantages to the plan.

Question: Is there anybody who supports you carrying out the IPUPP?

"*I've not asked anybody around so nobody's shown any interest in what I'm doing or anything like that, so no I don't think there is anything there that could happen there".*

It could be suggested there was a lack of understanding of the purpose of the plan, and skin health in general. He indicates the nurses were not aware of the plan, and he didn't receive much support in carrying out the plan.

Question: Is there anything that would it easier to carry out the IPUPP?

"I am reluctant to look after myself in a way. Which is stupid"

He also explained that he had not been conscious of his skin before, and had not yet adapted to looking after his skin health generally.

6.1.3 Participant 9

P9 was monitored for 2 nights and 1 day, which occurred 3 weeks after the timepoint 1 assessment. Table 6.7 shows significant improvement in 3 of the 4 parameters, namely, the maximum time between MOVAs in both lying and sitting positions and the average number of MOVAs per hour in the lying position. By contrast, there was no recorded MOVAs per hour in the sitting position at timepoint 2 in this participant with a high cervical injury with very limited function. Indeed, at both timepoints P9 required full assistance to reposition in the bed, and had compromised mobility to perform pressure relieving activity in the chair.

Table 6.7: Comparison of movements at timepoints 1 and 2 for P9, as determined by continuous pressure monitoring in both lying position and sitting position.

Measure	***Timepoint 1***	***Timepoint 2***	***Outcome***
Maximum time (min.) between MOVAs - lying	**516**	**440**	**Improvement**
Maximum time (min.) between MOVAs - sitting	**242**	**207**	**Improvement**
Average number of MOVAs - lying	**0.10**	**0.18**	**Improvement**
Average number of MOVAs - sitting	0.07	0.00	No improvement

Specific recommendations in the IPUPP for P9 included forward leaning while resting his hands on his knees every two hours. The temporal profile in the pressure parameters in the sitting position as illustrated in Figure 6.4 reveals that the improvement in maximum time between MOVAs is actually due to transfers on/off the wheelchair as opposed to an increase in pressure relieving activity. This can be most clearly seen in the profiles for peak pressure and contact area (Figure 6.4 A and B). There appears to be no effective pressure relieving activity performed during the pressure monitoring for timepoint 2. This indicates that P9 needed further support in finding effective pressure relief due to his high level of injury and associated low level of functionality.

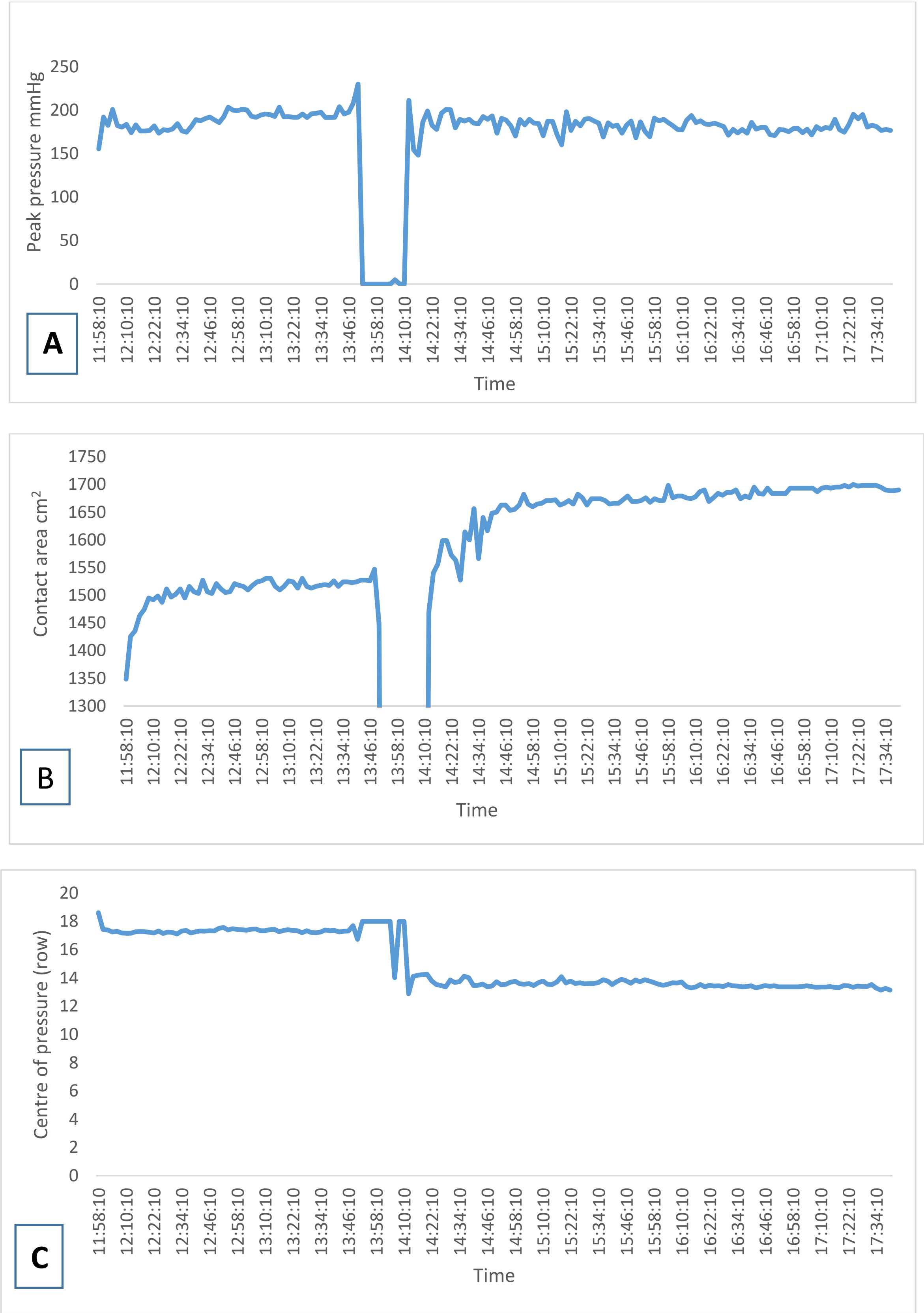


Figure 6.4: Temporal profiles of (A) Peak pressure (B) Contact Area and (C) Centre of Pressure row for P9 at timepoint 2, during the first day of pressure monitoring on a fluid-air cushion while sitting.

Further recommendations for P9 included 3-6 hourly turns while lying on a mattress, which compares with periods of between 3 and 8 hours estimated from the pressures recorded at timepoint 1. Table 6.8 shows that the maximum between MOVAs reduced by 15% from 516 mins (8 hours 35 minutes) at timepoint 1 to 440 mins (7 hours 19 minutes) at timepoint 2. This improvement following the PIUPP plan for P9 may be attributed to his previous experience of bed rest due to skin damage. Nonetheless, the participant still demonstrated prolonged periods of inactivity, as demonstrated in Figure 6.5, by an absence of amplitude changes in the centre of pressure in either orthogonal direction, during the early periods of night monitoring.

Table 6.8: Summary of movements on day 1 at timepoint 2 for P9, as determined by continuous pressure monitoring an air mattress in lying.

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	440	04:13:01	10	**Right side lateral> Left side lateral**
2	280	09:03:06	15	**Left side lateral> Supine**
3	35	09:53:07	30	**Back> Left side lateral Supine**
Transfer off bed	84	11:47:25	-	-

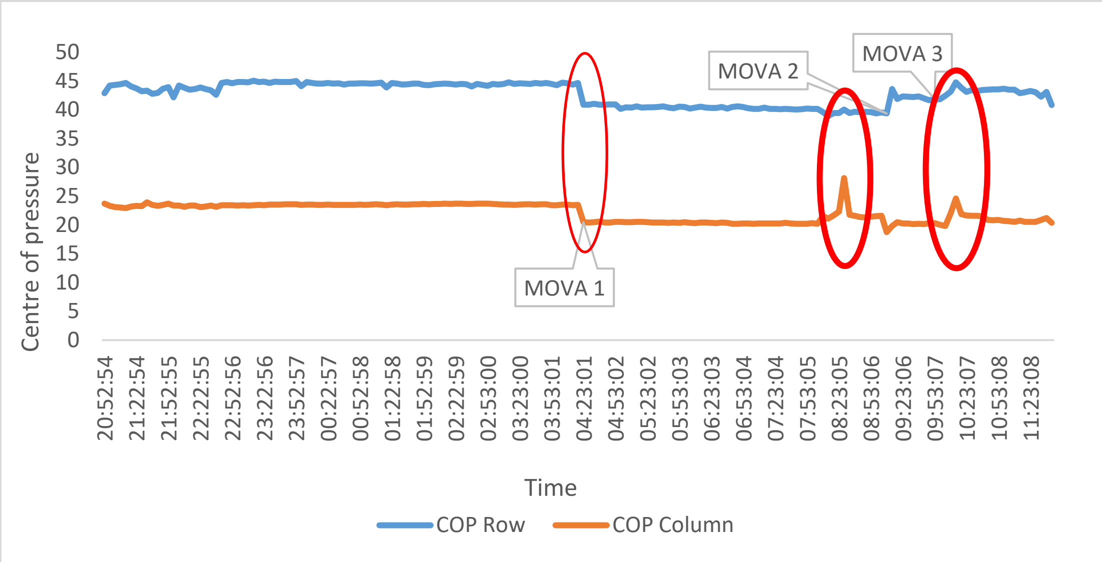


Figure 6.5: Temporal profiles of Centre of Pressure row and column for P9 at timepoint 2, during the first night of pressure monitoring on an air mattress in lying.

Interview with P9

***Question:* Is there anything you particularly like or dislike about the IPUPP?**

"Um the advice in it, erm, it's something I been thinking I'll be sticking to anyway. So that yeah I think that's the main thing is the advice

P9 appeared to appreciate the recommendation offered as part of the IPUPP. He had no particular dislikes regarding the plan.

Question: Are there any advantages or disadvantages to the IPUPP?

"Yeah I mean to me, because of my skin being as it was, and I've been doing the 6 hour turns for probably about 4-5 week probably a bit longer, and I think that's definitely for me, the way to go".

P9 went on to say *"Weight shifting I've been having a little go at that lately, and it doesn't give me any bad benefits so, yeah it's all good"*

He had a clear understanding of the advantages of the plan, regarding skin health, and could relate this to previous skin problems. He also spoke of weight shifting in the chair although, as previously discussed, this was an issue for him due to low levels of function,

6.1.4 Participant 10

P10 was monitored for 2 nights and 1 day, which occurred 9 weeks after the timepoint 1 assessment. Table 6.9 indicates a consistent finding for all four parameters, namely, an increase in the maximum time between MOVAs and a decrease in the number of MOVAs per hour at timepoint 2 for both sitting and lying positions. P10 presented with a low thoracic injury and, consequently, had full use of arms, hands and good trunk control to assist with movement and transfer.

Table 6.9: Comparison of movements at timepoints 1 and 2 for P10, as determined by continuous pressure monitoring in both lying position and sitting position.

Measure	***Timepoint 1***	***Timepoint 2***	***Outcome***
Maximum time between MOVAs – lying	165	235	No improvement
Maximum time between MOVAs - sitting	116	258	No improvement
Average number of MOVAs - lying	0.59	0.41	No Improvement
Average number of MOVAs -sitting	0.56	0.14	No Improvement

Specific recommendations in the IPUPP for P10 included side to side leans of 2-3 minutes duration every 2 hours, as an alternative to leaning forwards which the participant could not achieve without pain. This advice was clearly not followed as demonstrated by the data in Table 6.10. Indeed, there was only one pressure relieving activity in the sitting position, which lasted for 4 minutes. This resulted can be seen in temporal profiles for contact area and the centre of pressure in both orthogonal directions, as illustrated in Figure 6.6. No specific recommendations were provided for P10 in the lying position.

Table 6.10: Summary of movements on day 1 of timepoint 2 for P10, as determined by continuous pressure monitoring on fluid/foam cushion in sitting.

MOVA	**Time since previous MOVA *(mins)***	**Time started**	**Duration *(mins)***	**Description**
1	258	16:45:56	4	**Right side lean**
Transfer off bed	172	19:42:10		

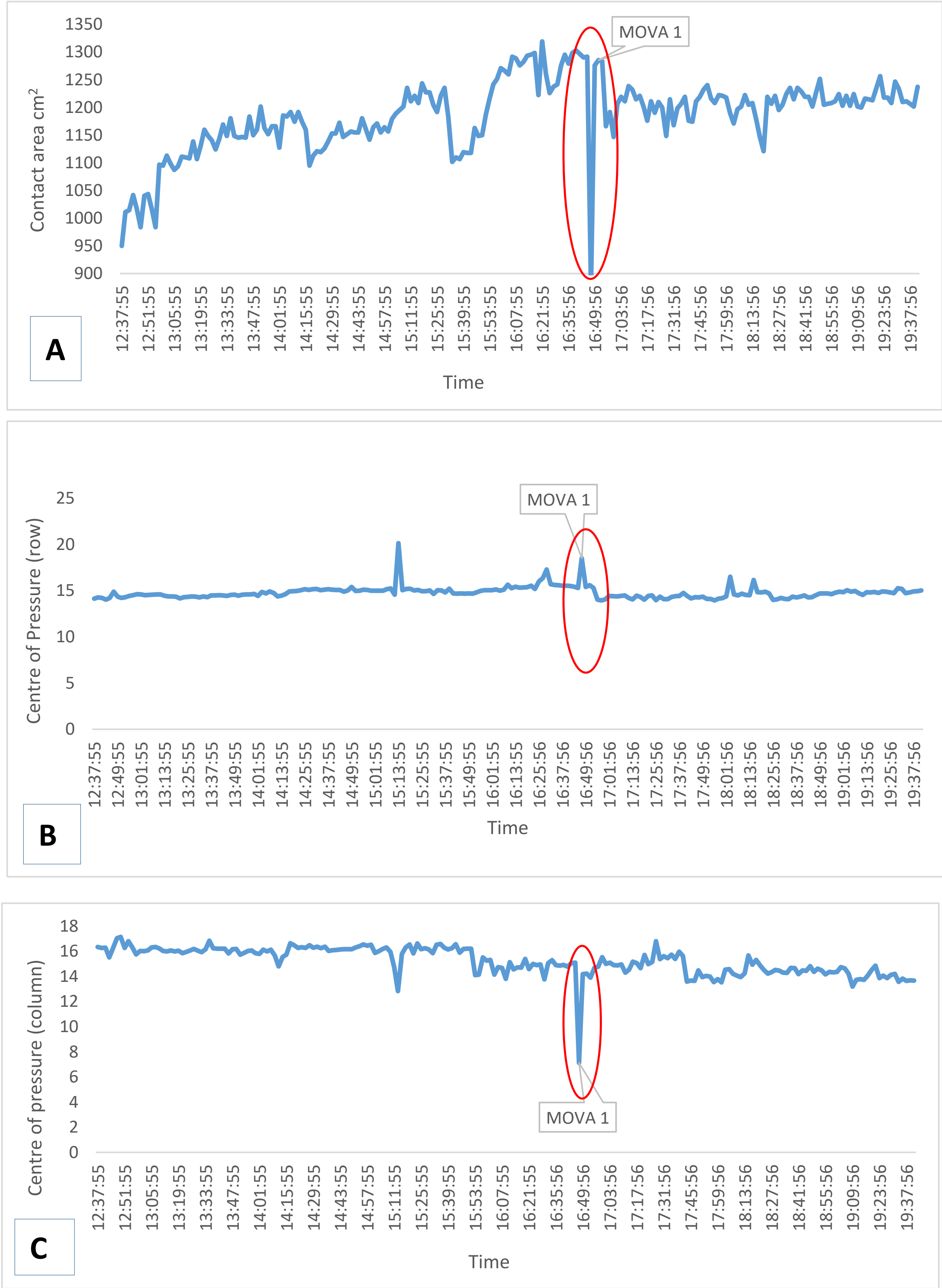


Figure 6.6: Temporal profiles of (A) Contact Area (B) Centre of Pressure column (C) Centre of Pressure, row for P10 at timepoint 2, during day 1 of pressure monitoring whilst sitting.

Interview with P10

Question: Is there anything you particularly like or dislike about the IPUPP?

"I've been more aware of the need to move around".

P10 the IPUPP process had him more aware of the need to perform pressure relieving activity, He did not express any particular dislikes.

Question: Are there any advantages or disadvantages to the IPUPP?

"So you know, ignorance is not bliss is it, so knowledge is".

He had a clear understanding of the advantages of following a plan, and found knowledge gained through the long term pressure monitoring was useful.

Question: is there anybody who supports you in carrying out the IPUPP?

"But I always thought they were doing it on a routine basis, but they don't seem to, they don't have time".

P10 also suggests the nurses do not routinely check his skin, although he sometimes asked them to,

It is notable that P10 presented with a low level injury and had not experienced prior bed rest due to skin issues. It might be suggested that he was considered by the nursing staff to be at "low risk" for skin-related damage.

6.2 Analysis of cohort

Although the number of participants who were monitored on two occasions in the hospital setting were limited, a more comprehensive statistical analysis of the movement-related parameters could still be performed. In particular, descriptive statistics for both movement parameters were estimated for each of the four participants. The maximum times between MOVAs in terms of the median and range for both lying and sitting positions are summarised in Table 6.11. It revealed the considerable variation in the maximum times at both timepoints 1 and 2. An alternative presentation of this data involves the frequency distribution between MOVAs in hourly increments in both the lying and sitting positions, as shown in Figures 6.7 and 6.8, respectively. No consistent trend was evident for any of the variables. However, it might be noted that participant P1 demonstrated a similar distribution at both timepoints when monitored in the lying position (Figure

6.7A), whereas, in sitting, there was significant higher number movements of less than 1 hour at timepoint 2 (Figure 6.8A). By contrast, participant P10 moved 10 times within three-hour threshold at timepoint 1 compared to only one movement within the same time frame at timepoint 2 in the sitting position (Figure 6.8A)

Table 6.11 Descriptive statistics of maximum time between MOVAs for the four participants as estimated from in both lying and sitting positions at timepoints 1 and 2.

	P1	P4	P9	P10
	Median (range) – mins.	Median (range) – mins.	Median (range) – mins.	Median (range) – mins.
Lying Timepoint 1	183 (15-326)	131 (19-311)	382 (115-516)	100 (15-165)
Timepoint 2	237 (55-360)	164 (49-285)	280 (35-440)	87 (24-235)
Sitting Timepoint 1	219 (101-230)	135 (96-160)	176 (96-243)	50 (26-116)
Timepoint 2	39 (10-141)	77 (20-427)	156 (104-207)	215 (172-258)

Lying data

Timepoint 1 **Timepoint 2**

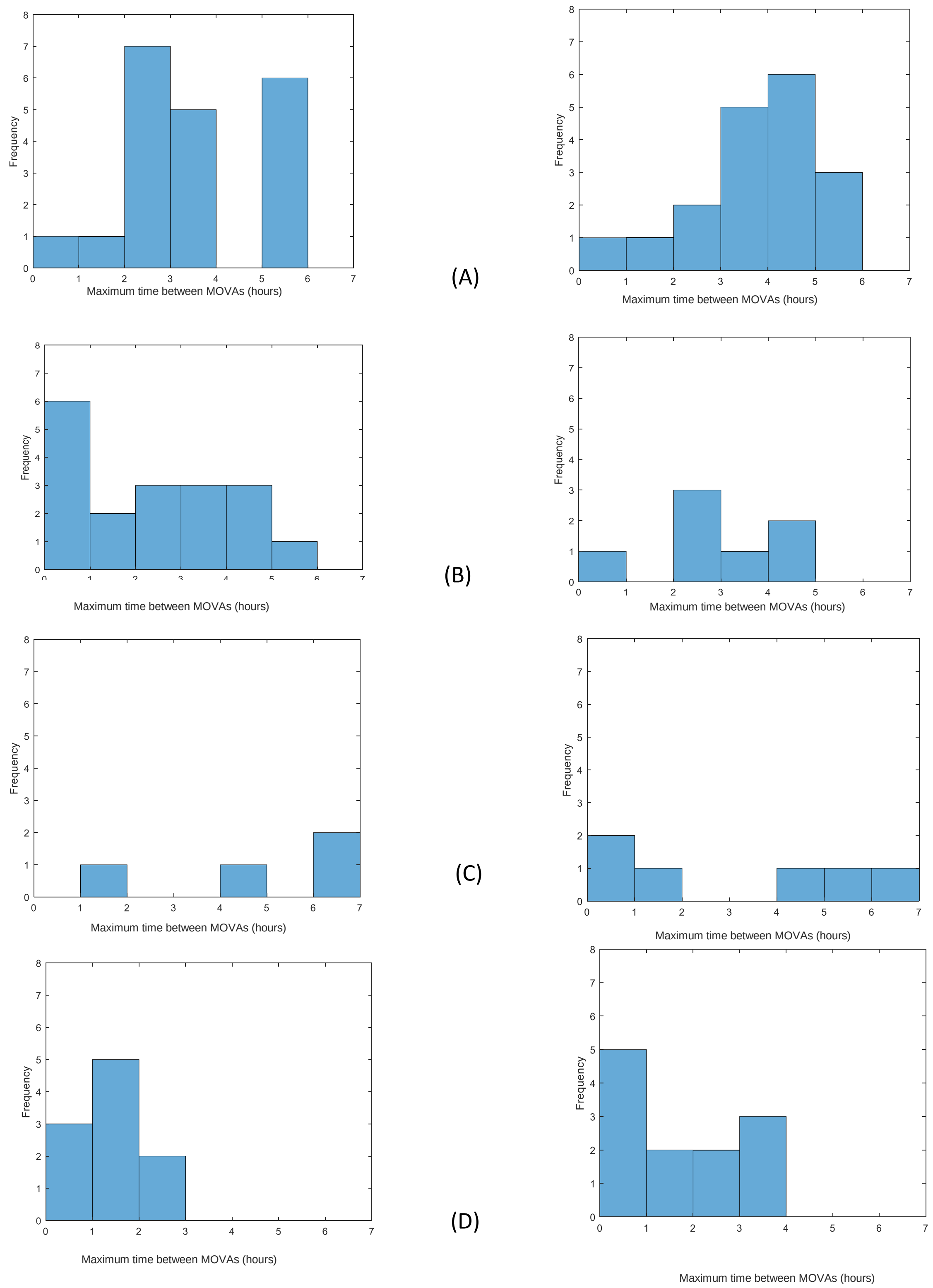


Figure 6.7: Hourly distribution of the times between MOVAs during lying at timepoint 1 and timepoint 2 for participants (A) P1, (B) P4, (C) P9 and (D) P

<u>Sitting</u>

Timepoint 1 **Timepoint 2**

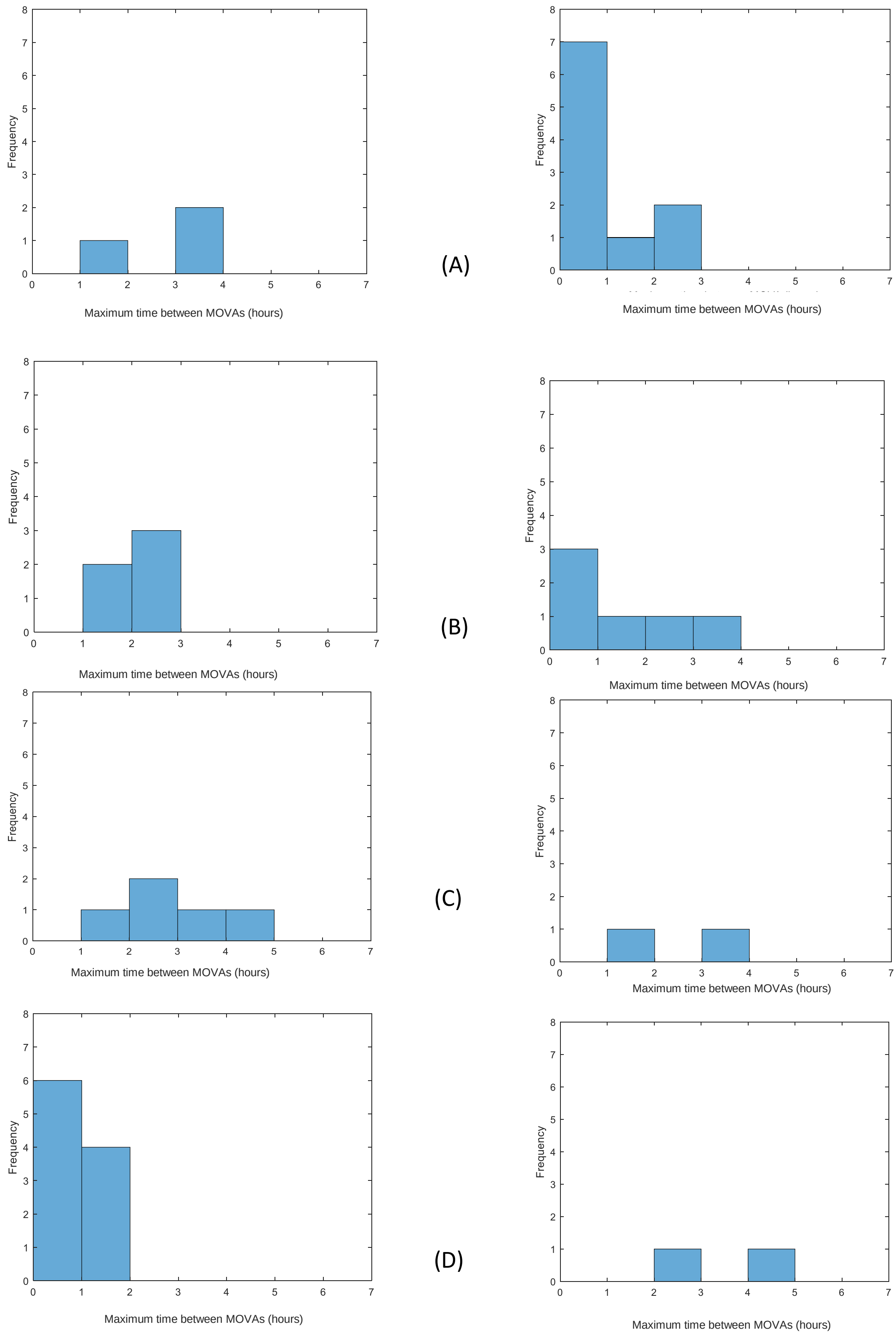


Figure 6.8: Hourly distribution of the times between MOVAs during sitting at timepoint 1 and timepoint 2 for participants (A) P1, (B) P4, (C) P9 and (D) P10.

An alternative presentation in Table 6.12 summarises the number of continuous or static postures for each participant which exceeds 3 hours in both lying and sitting. In terms of lying, it is evident there no improvement prolonged lying postures in 3 of the four participants between timepoint 1 and 2 (P1, P9 and P10). It is evident there was some improvement for prolonged lying postures for P4. It is notable that P4, who has low thoracic injury, has use of upper limbs and can manage postural changes in lying. As previously mentioned, this improvement in lying did not translate to improvement in sitting postures. An interesting result shows that P1 and P9 did improve in terms of prolonged postures during sitting. This is despite the fact that both P1 and P9 both have injuries above T6, therefore restricted use of upper limbs. This is discussed further in section 6.5.

Table 6.12: The number of postures exceeding three hours between MOVAs for the four participants who were monitored in lying and sitting positions at time points 1 and 2.

	P1	P4	P9	P10
Lying Timepoint 1	10	7	4	0
Timepoint 2	13	3	4	3
Sitting Timepoint 1	2	0	2	0
Timepoint 2	0	2	1	1

6.3 Discussion

It was evident that the original intention of assessing movement behaviour following individual IPUPP strategies was determined by the availability of the original cohort of participants in the SCI unit which became influenced by the extraordinary situation associated with the pandemic. This reduced the number available for timepoint 2 to four participants. These had been forced to remain in hospital due to a series of factors including their co-morbidities, accommodation and financial-based issues

There were considerable differences when participants were monitored at timepoints 1 and 2. For example, two participants, P1 and P9, demonstrated some improvement in three of the 4 movement parameters (Tables 6.2 and 6.7). However, close examination revealed that the reduction in maximum time between MOVAs for P9 in the sitting position was due to frequent transfer off the chair in this active SCI subject, as opposed to the introduction of additional pressure-relieving activities associated with the IPUPP. Nonetheless, P9 did show evident improvement in pressure relieving activity in the lying position (Table 6.6). By contrast, P4 and P10 showed minimal or no improvement (Tables 6.5 and 6.9).

When examining the sitting data, a factor that remained particularly similar across timepoints 1 and 2, was posture. P4 and P9 demonstrate clear pelvic obliquity to the left side in both timepoints (Figure 6.9 and 6.11). Although this was raised to other members of the MDT, the issue remained prevalent throughout their stay in the SCI unit. With regards to posture, P10 demonstrated 3 areas of high pressure, which may indicate leaning onto the left greater trochanter (Figure 6.10).

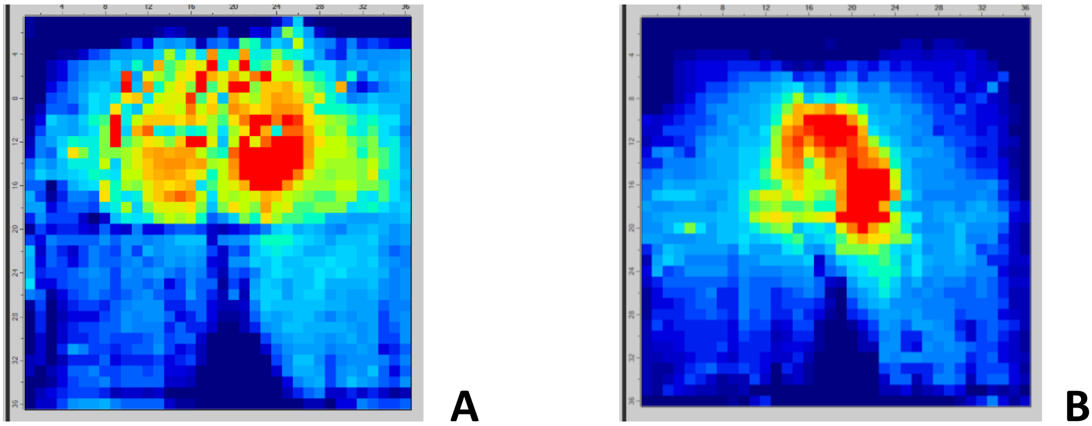


Figure 6.9: Pressure distributions of P4 in the sitting position showing pelvic obliquity to the left side in (A) Timepoint 1 (B) Timepoint 2

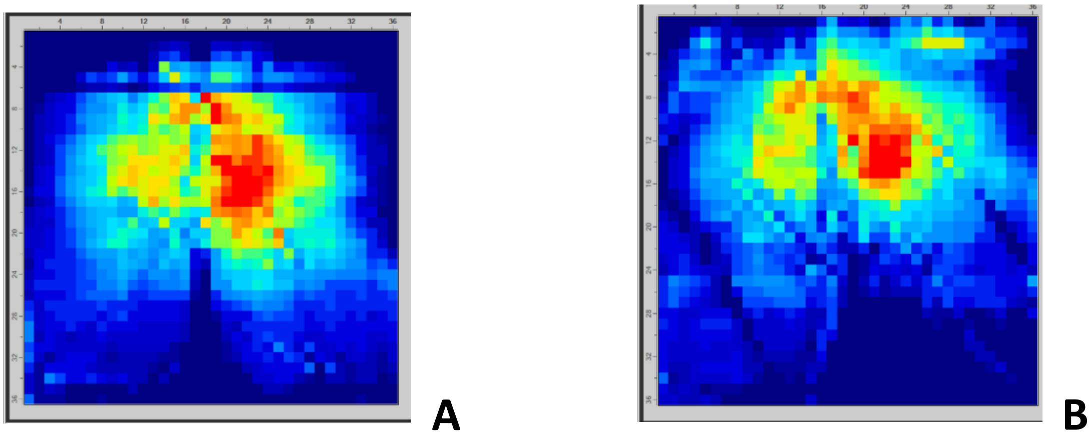


Figure 6.10: Pressure distributions of P9 in the sitting position showing pelvic obliquity to the left side in (A) Timepoint 1 (B) Timepoint 2

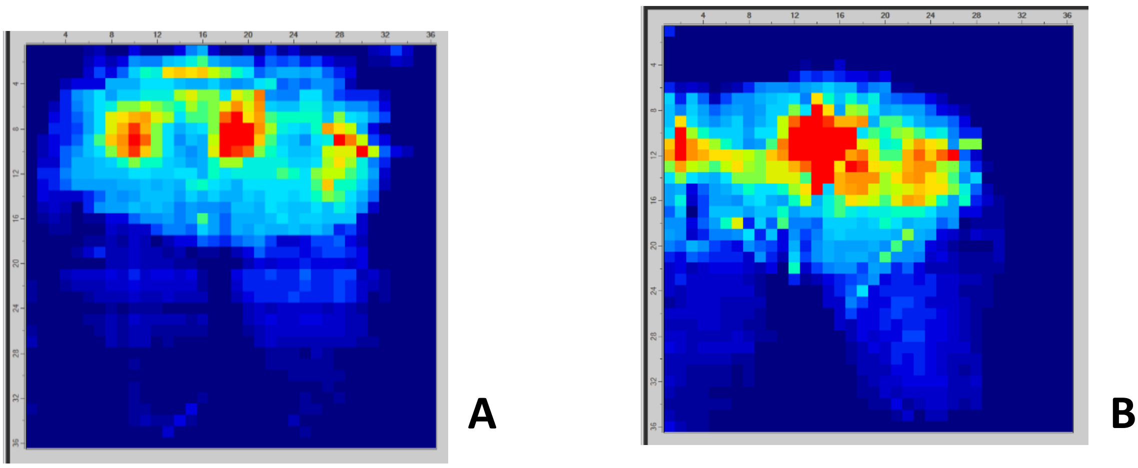


Figure 6.11: Pressure distributions of P10 in the sitting position indicating leaning towards the left trochanter (A) Timepoint 1 (B) Timepoint 2

From these findings, it might be inferred that the overall outcome of the intervention associated with the IPUPP are inconsistent. It is noted that P4 and P9 presented with a higher level of injury, and have previously experienced bed rest due to skin damage (Table 5.2). They also appeared most engaged, when discussing the IPUPP at interview. It is also accepted that sitting posture offers a complex and challenging aspect of PU prevention, which requires an engaged and consistent approach from all members of the MDT and must also consider both postural and functional aspects.

It should be noted in the two years after SCI, there are many changes to environment. Essentially, a person with spinal cord injury (PWSCI) moves from an acute hospital ward, to a rehabilitation facility, to a community placement or private residence within an 18-24 month period. It would reasonable to suggest that this constant change of environment makes learning and developing new skin health habits more difficult.

It is relevant that rehabilitation after SCI is a complex process psychologically. Low morale and potential suicidal thoughts may be particularly prevalent during the first years after SCI, although these features tend to abate over a 5 year period (Tchajkova et al. 2021). Nonetheless, it is inevitable that over the timepoints of assessment as an in-patient, the individual ability to engage and overall motivation will vary considerably. As an example, P4 seemed to have not yet fully accepted the longevity of the spinal cord injury at timepoint 2. This was apparent when talking about his physiotherapy with the statement, “I’ll battle it for two to three years and let’s see how we are then. Hopefully if I’m no, no better, crikey I will have packed up, but err if there’s any chance of a spark there, I will just keep slogging away”. He also suggested he would find it difficult to adhere to the IPUPP if the timeframe was open-ended. “I’d like times that are not open ended you know”. This indicates that P4 had not fully adapted to the chronic injury at this time. This potentially affected motivation to engage with skin health. This may have been the main reason why P4 did not show improvement between timepoint 1 and 2.

It can be concluded that the impact of the IPUPP are inconsistent, in terms of pressure monitoring parameters. However, it appears those who have experienced bed rest due to skin health issues are more likely to be engage with the process. This is discussed further in Chapter 8.

6.4 Summary of key findings

- Repeated continuous pressure monitoring after implementation of IPUPP produced inconsistent results

- Participants who had previously experienced bed rest to due skin health were more likely to engage with the IPUPP
- Adjustment and acceptance of injury could possibly effect motivation to engage with skin health.
- Pelvic obliquity can remain a prolonged issue for PWSCI during inpatient rehabilitation

Chapter 7 Timepoint 3 results- Long term pressure monitoring in the community setting

This chapter will investigate frequency and magnitude of movement after discharge to the community. Participants with spinal cord injury (SCI) were discharged to a variety of settings, including home, nursing home or neuro-rehabilitation centre. Discharge setting was dependent on factors such as finances, renting or owned property, care needs and living alone etc. This is discussed further in Chapter 8. The monitoring occurred at a time that was agreed by the participant and researcher. The data collection process was deemed safe by the NHS trust in terms of COVID precautions and lone worker policy. Infection prevention protocols for the equipment (cleaning) and researcher (personal protective equipment) were implemented. Table 7.1 demonstrates the discharge destination of each participant, in addition to months post injury and weeks post discharge. The former ranged considerably (7-18 months), which was associated with patient health, access to social care support and length of hospital stay. Two patients were lost to follow up due to withdrawal from study in time-point 1 (P3) and self-isolation due to COVID 19 (P9).

7.1 Participants

Table 7.1: Timepoint 3 participant discharge information

Participant	***Level***	***ASIA***	***SCI function Score***	***Discharge destination***	***Months post injury***	***Weeks post discharge***
1	T6	A	19.5	Home	18	4
4	T10	A	23.5	Home	11	25
5	T11	D	41	Home	10	17
8	T4	D	34	Nursing Home	7	4
10	T11	A	24.5	Nursing Home	16	30
11	C4	B	15	Neuro rehab centre	17	30
12	L2	B	33	Home	8	14
13	C5	B	16	Home	18	32
14	C8	B	19	Home	12	27
15	T11	A	24.5	Home	13	34

Table 7.2 demonstrates the support surfaces participants were using during time point 3 monitoring. In a number of cases there were changes in the type of support surface between inpatient and community settings (Table 5.2). This was informed by discharge planning with the multidisciplinary team, access to community resources. It is of note that two participants were provided with turning

assist systems (ToTo), used laterally tilt individuals in bed. The corresponding pressure profiles will be assessed in the Chapter.

Table 7.2: Timepoint 3 support surface information

ID	***Support surface –lying***	***Repositioning Aid***	***Support surface -sitting***	***History of Community Skin Damage***
1	Talley Quatro plus(air)	**+TOTO**	Jay balance, roho insert (foam + air insert)	YES (Serious illness)
4	Invacare premier spinal (castellated foam)		Invacare matrx flocare (foam)	NO NO
5	Foam		Not using wheelchair	NO
8	Invacare softform premier spinal (foam)		Matrx VI (Foam)	
10	Softform premier pro Castellated foam)		Axion SP	NO
11	Air		Foam with roho insert (foam+ air insert)	YES
12	Orthopaedic spring mattress		Jay 3 (Foam)	NO
13	Foam	**+ TOTO**	Starlock (air)	NO
14	Orthosoft vision delux		Roho Hybrid (air/foam)	NO
15	Mecure (Foam)		Vicair O2 active 6	NO

7.2 Timepoint 3 Case Studies

Consistent with Chapter 5, three case studies (#P5, #P11 & #P13) will be reported in depth detailing movement to offload vulnerable areas (MOVA) and pressure profiles. These were selected to represent those with high (P5) and low (P11, 13) level of function. The method of analysis detailed in Chapter 4 was employed for all participants. Participants were discharged with different care plans. These plans range from no carers, outpatient follow up (P5) alone to 2 x daily carers (P13) or full care in a neuro-rehabilitation centre (P11). The input required from carers is often determined by the level of injury, severity of injury and co-morbidities

7.2.1 Participant 5

P5 was 67 years old at the time of monitoring, which took place in December 2019. Due to participant preference, P5 was pressure monitored 17 weeks post discharge. She was 10 months post injury at T11 level and was assessed as ASIA D. At the time of community monitoring she was independently mobile with a zimmer-frame, spending periods between a leisure chair and bed. The participant had intact sensation and power in their upper limbs and was able to both reposition herself in bed and self-transfer to a leisure chair. As described in Chapter 5, had cardiac co-morbidities, including Aortic Fistula and Bi-illiac Aneurysm.

Skin assessment

She had a history of moisture associated skin damage (MASD) on her ischial tuberosities which resolved with bed rest. At the time of assessment, there was no skin damage.

Support surfaces and transfers

Pressure monitoring occurred on a castellated foam mattress (Invacare Softform Premier) whilst in bed and a leisure chair in sitting.

Timepoint 3 showed that P5 had different pattern of movement from previous periods of monitoring, and that of the other participants. Whereas previous monitoring showed evidence of static periods with intermittent period of pressure relieving activity (Table 5.6), timepoint 3 monitoring showed regular changes in position whilst seating, stimulated by sensation. There are also regular intervals in the monitoring where P5 could stand from the chair and walk with the Zimmer frame; these are outlined in Table 7.3. The data revealed standing/walking intervals, which had a corresponding effect on peak pressure and contact area, with periods of no signal, demonstrated in Figure 7.1. Pressure distributions are demonstrated in Figure 7.2.

Table 7.3: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1.

Night	***Time monitoring started***	***Monitoring period on mattress (mins)***	***Number of MOVAs***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	22:16:38	458	2	55	195
Day	***Time monitoring started***	***Monitoring period on cushion (mins)***	***Number of walking Intervals***	***Minimum time between walking intervals (mins)***	***Maximum time between MOVAs (mins)***
1	11:04:17	537	4	43	222

7.2.1.1 Monitoring lying data (night 1)

P5 was monitored for 8 hours and 57 minutes on night 1. It was evident from the temporal profiles of each of the three pressure parameters that P5 turned herself frequently, with static periods ranging 55 to 195 minutes in duration. Pressure parameters from night 1 monitoring are presented in Figure 7.1. The figures revealed limited movements over a 6 hour period including two MOVAs. It is also evidence that there are no smaller perturbations in the data, indicative that there are very few postural adjustments during the night. There is small decrease in frequency of movement during sleep between timepoint 1 and 3, including a 20 minute increase in maximum time between MOVAs and a decrease in average number of MOVAs.

Table 7.4: Summary of movement, P5, night 1 of pressure monitoring, timepoint 3.

MOVA	***Maximum time between MOVAs***	***Time started***	***Duration***	***Description***
1	55	00:15:00	20	Right side lateral> Supine
2	110	02:25:02	15	Supine> Left side lateral
Transfer off seat	195	05:55:05		

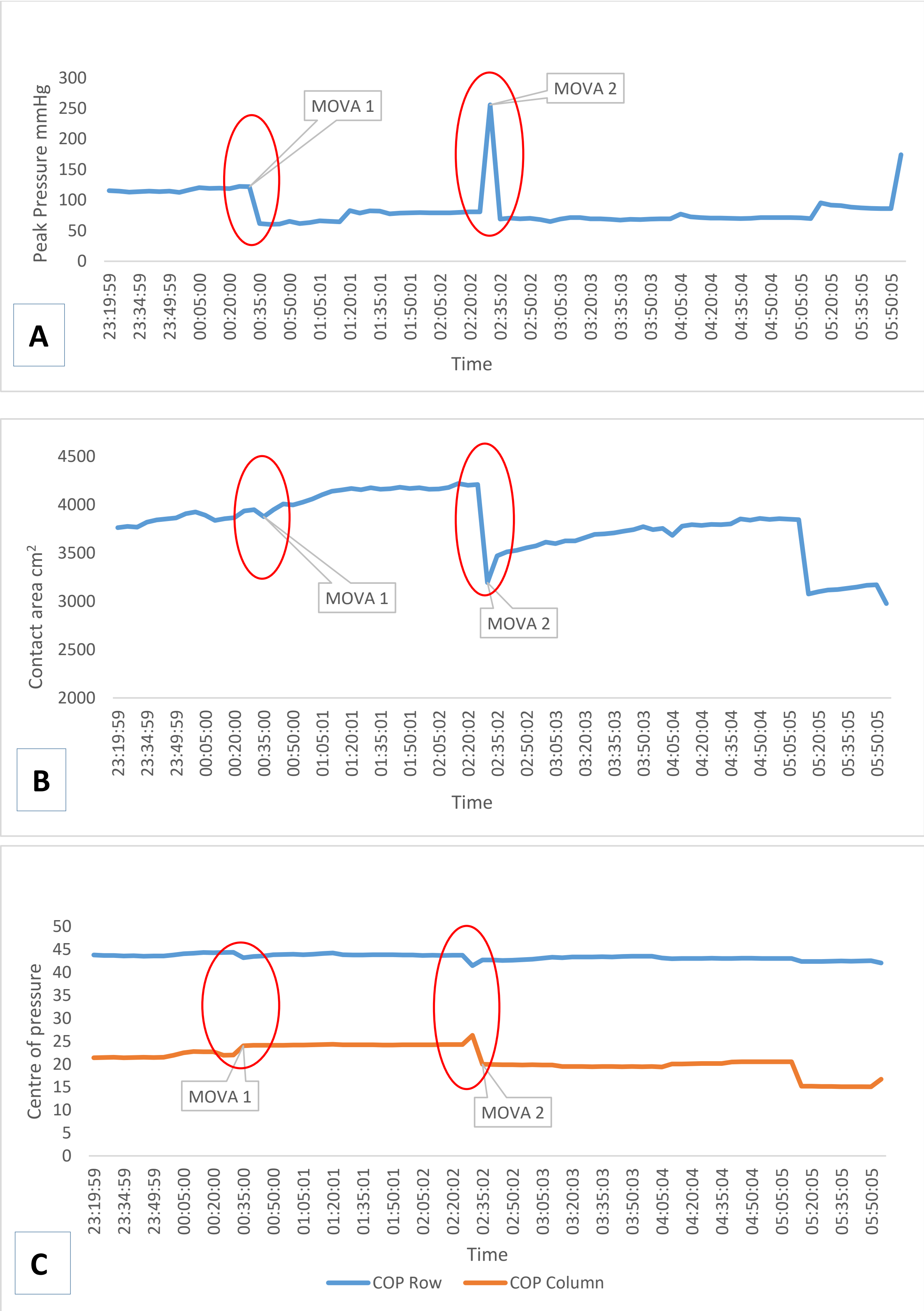
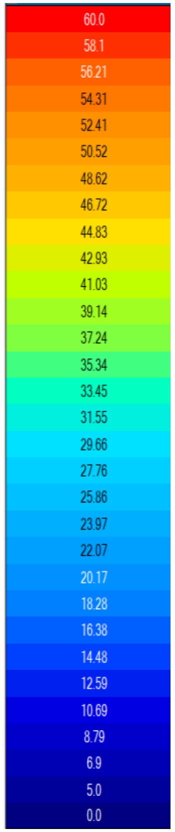


Figure 7.1 Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row and column for P5 at timepoint 3, night 1 of pressure monitoring on mattress

MOVA 1 **MOVA 2**



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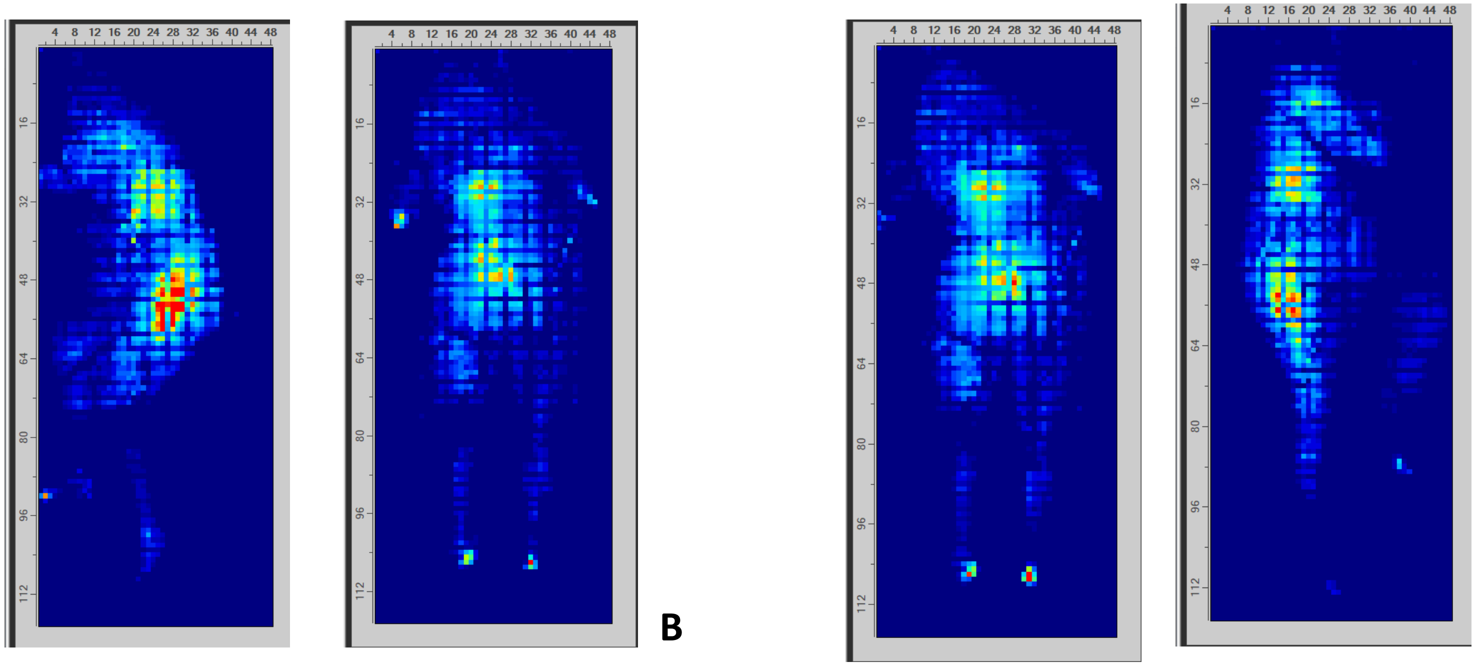


B C

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
00:15:00	119	3843	44	22
00:35:00	60	3848	43	23

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
02:25:02	80	4211	43	24
02:40:02	71	3510	42	19

Figure 7.2: (A) pressure scale ranging from 5-120mmHg. Pressure distribution and corresponding pressure parameters on (B) right side lateral to supine during MOVA 1. (C) Supine to left side lateral during MOVA 2,P5, timepoint 3, night 1 of mattress monitoring

The pressure profiles detailed in Figure 7.2, correspond to a movement from left lateral to supine (MOVA 1) and a return to lateral lying (MOVA 2). The resulting peak pressure areas move from that of the greater trochanter and shoulder to the sacrum and thoracic spine (supine). The corresponding peak pressure values change between postures with peak pressures reducing by 59mmHg. This was associated with higher pressures being evident on the greater trochanter during lateral lying and a more evenly distributed pressure during supine. The changes in contact area and COP are more evident during MOVA 2, observed in the temporal data of these parameters presented in Figure 7.1. The castellation in the foam mattress can also be observed in the pressure profile, depicted by linear lines in the pressure profiles in the inferior-superior and medial-lateral directions.

7.2.1.2 Monitoring seating data

P5 self-transferred to a leisure chair using her Zimmer frame to transfer on an off independently. The pressure distribution in the sitting posture, as illustrated in Figure 7.4, reveals a symmetry of pressure distribution with no evidence of sacral sitting or pelvic obliquity. However, there are two clearly defined areas of pressure gradients, corresponding to each ischial tuberosity (Figure 7.4). Four distinct MOVAs were observed during the seating monitoring period (Table 7.5).

Table 7.5: Sitting data. Standing/walking intervals, P5, day 1 of monitoring, timepoint 3

Interval number	***Start time***	***End time***	***Maximum time since last interval (mins)***
1	11:56:08	12:05:26	43
2	13:02:42	14:03:14	57
3	14:54:25	15:02:05	50
4	15:56:16	16:03:33	54
Transfer off seat	19:46:15		222

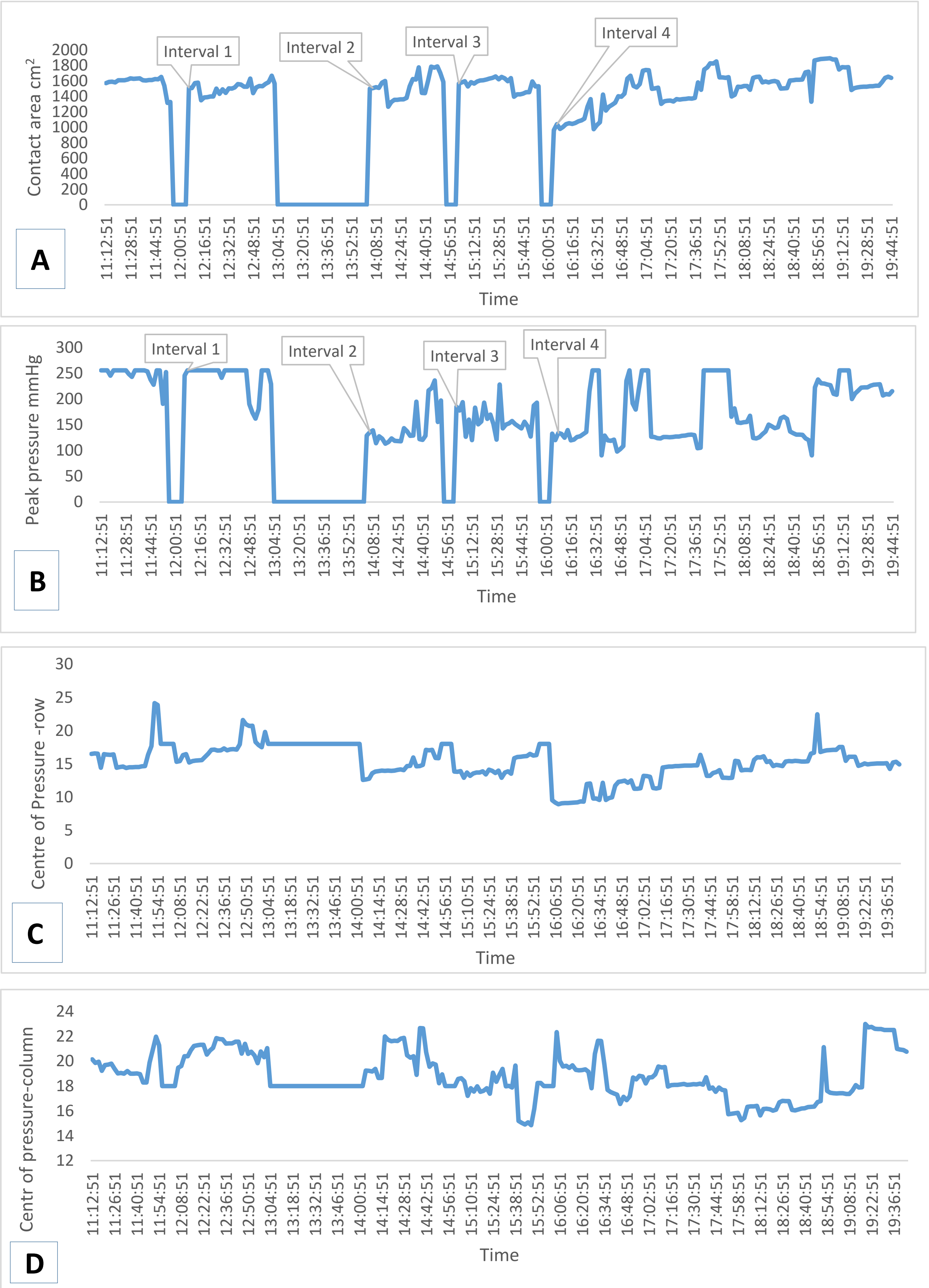
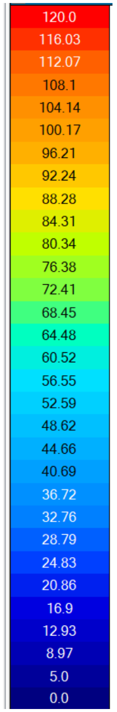
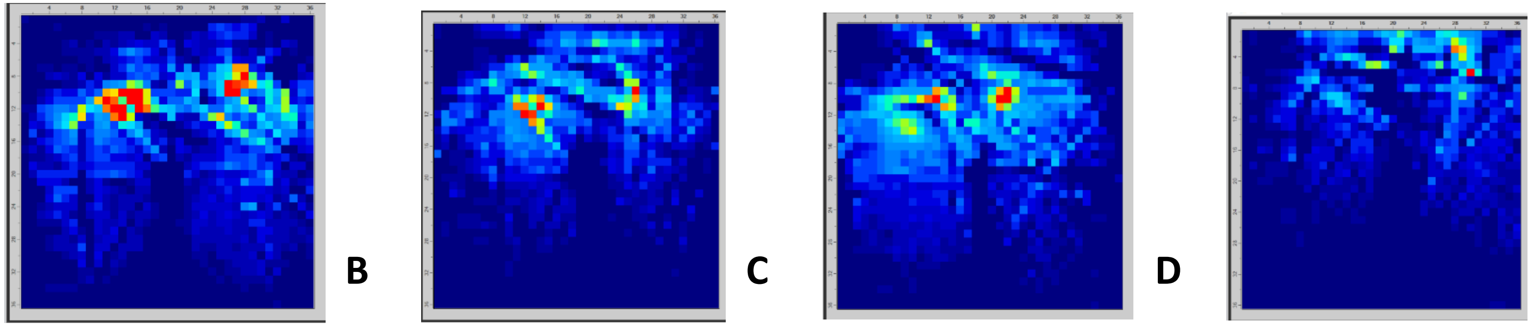


Figure 7.3: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) Centre of Pressure, column for P5 at timepoint 3, night 1 of pressure monitoring on mattress.

Walking/standing intervals- day 1



A 

Time	Peak Pressure (mmHg)	Contact Area (cm²)	Centre of Pressure Row	Centre of Pressure Column
12:05:06	221	1330	14	21
14:03:14	148	1111	11	18
15:02:05	156	1317	13	16
16:06:23	137	979	9	22

Figure 7.4: (A) Pressure scale ranging from 0 – 120 mmHg. Distribution of pressures and corresponding pressure values in sitting position after each walk standing/interval at (A) 12:05:06 (B) 14:03:14 (C) 15:02:05 p5, timepoint 3, day 1

7.2.2 Participant 11

P11 was 28 years old at the time of monitoring, which took place in November 2020. She was 17 months post injury and 30 weeks post discharge. She was at C4 level and was assessed as ASIA B. She had a low functional score, and required full assistance with ADL. At the time of community monitoring she had been discharged to Neuro-rehabilitation facility, whilst awaiting a permanent housing solution.

Skin assessment

Since previous monitoring, P11 experienced periods of bed rest due to skin damage, particularly in the gluteal fold. During the timepoint 3 monitoring her skin was checked by carers from the rehabilitation centre and once by the research nurse (SF). The skin damage in the gluteal fold was reported as healed. A dressing was still being applied to the area as prophylaxis. No other skin damage reported or observed during timepoint 3 monitoring.

Support surfaces and transfers

Due to ongoing skin problems, particularly recurrent skin marks in the gluteal fold. She was placed on an air-based mattress. She was a full hoist transfer, and used a foam/air wheelchair cushion.

Table 7.6: Summary of movement behaviour of P5 on foam mattress and wheelchair cushion at time point 1.

Night	***Time monitoring started***	***Monitoring period on mattress (mins)***	***Number of MOVAs***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	18:38:42	921		245	585
2	19:07:20	897		220	639
Day	***Time monitoring started***	***Monitoring period on cushion (mins)***	***Number of MOVAs***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	10:24:20	294	0	289	289

7.2.2.1 Monitoring lying data (night 1)

The maximum time between MOVAs increased, from 455 minutes to 639 minutes for timepoint 3 and 1, respectively. This is demonstrated in Table 7.6 and Figure 7.5 and 7.6. It is notable that the air mattress did not reduce peak pressure. Figure 7.7 illustrates peak pressure on night 1 of timepoint 1, peak pressures typically ranged between 40- 60 mmHg. By contrast, during time point 3 the corresponding values were 60-80mmHg (Figure 7.7). Temporal changes in the interface pressure parameters can be observed in timepoint 3 (peak and contact area), consistent with perturbations in pressure caused by an alternating air mattress. The pressure profiles (Figure 7.6) also clearly show the air cell distribution with horizontal lines evident on the spatial pressure image.

Table 7.7: Summary of movements for P11, night 1 of pressure monitoring, timepoint 3

MOVA	***Maximum time between MOVA (mins)***	***Time started***	***Duration (mins)***	***Description***
1	245	22:49:58	15	**Right side lateral> Left side lateral**
Transfer off bed	585	08:50:47		

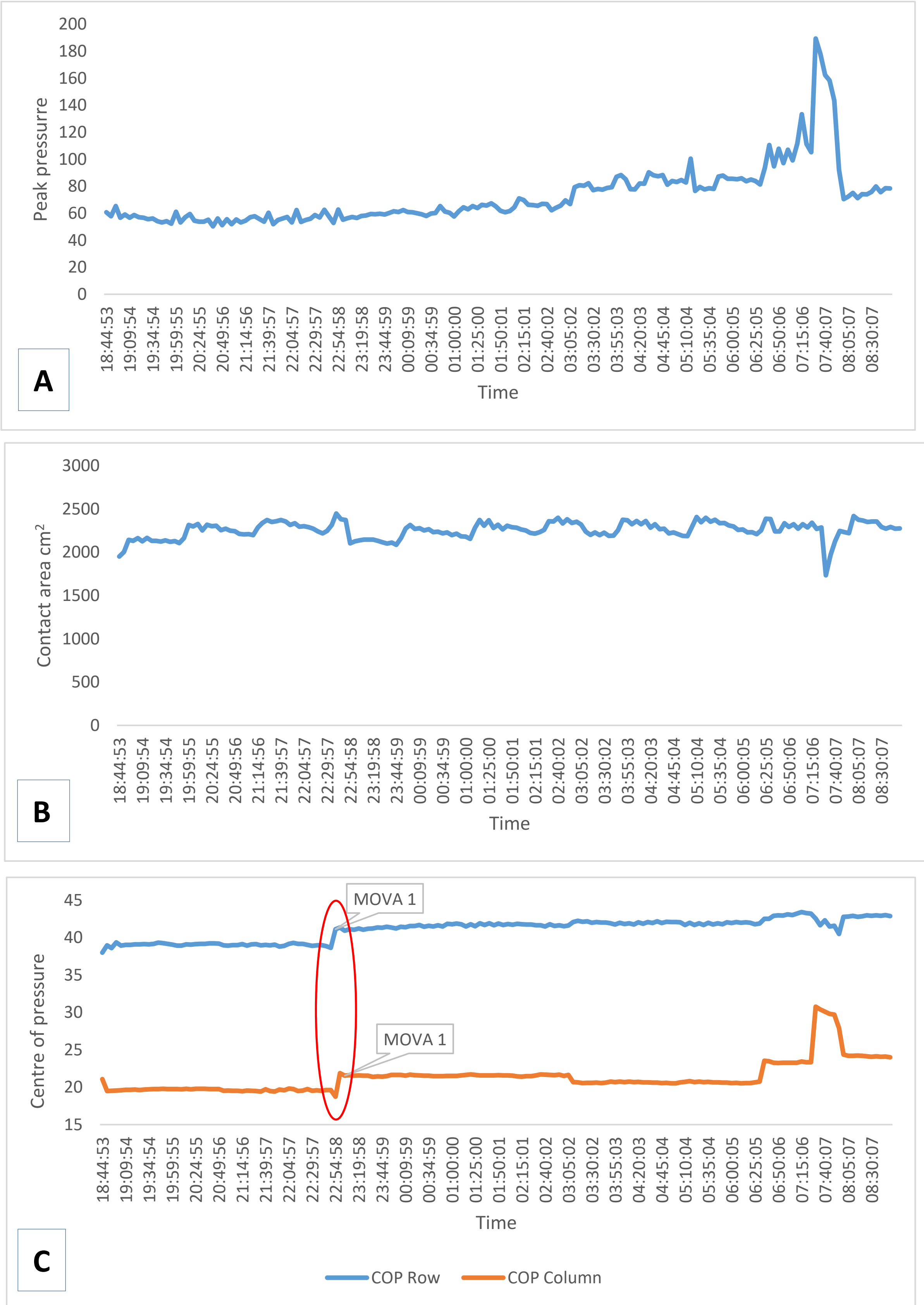
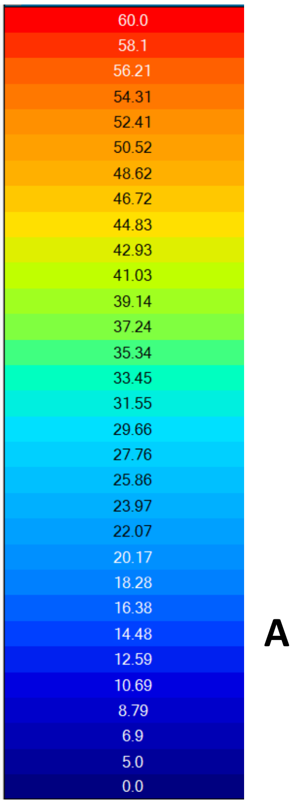
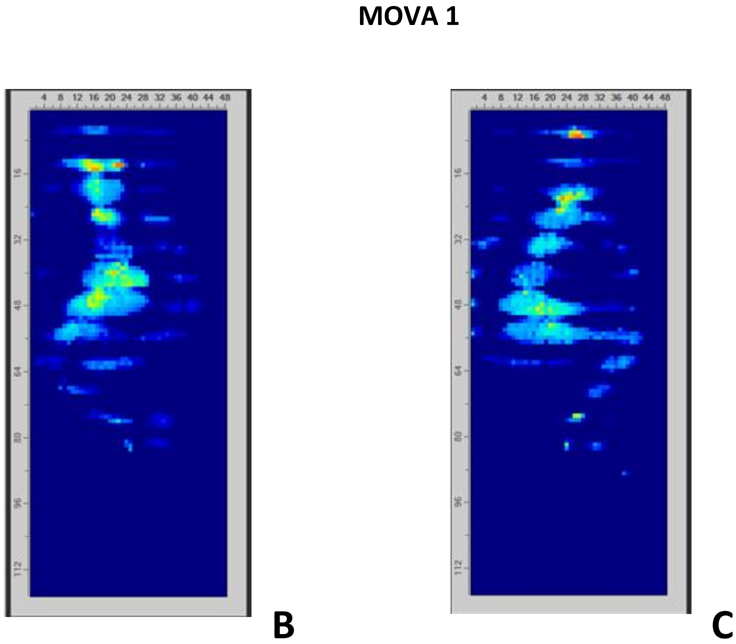


Figure 7.5: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) centre of pressure column for P11 on timepoint 3, night 1 of pressure monitoring on mattress





Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
10:49:58	55	2373	38	19
11:04:58	56	2134	41	21

Figure 7.6: (A) Pressure scale ranging from 0 – 60mmHg. Pressure distributions and corresponding pressure parameters for (B) right side lateral (C) left side lateral during MOVA 1.

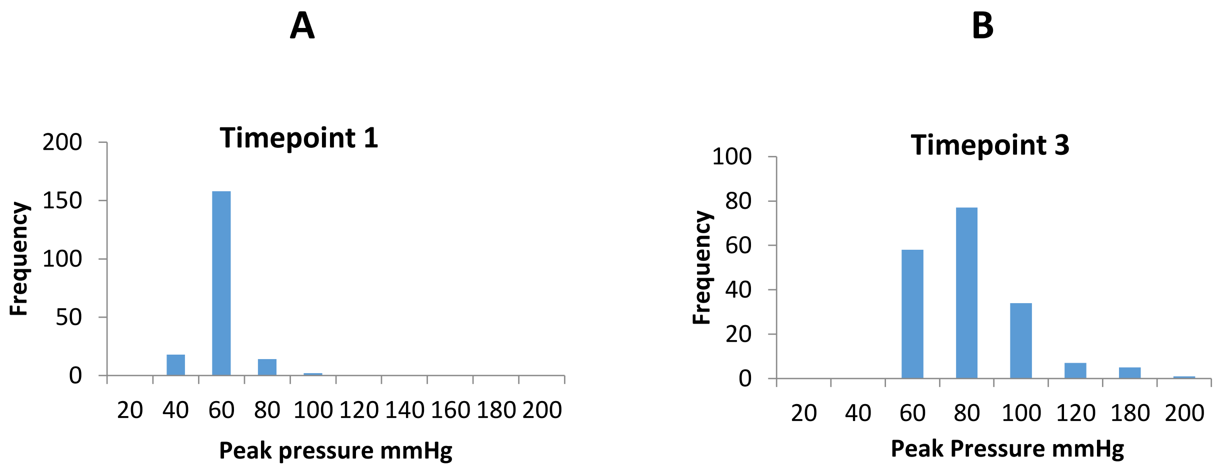


Figure 7.7: Histogram of peak pressure for P11, (A) night 1 of monitoring, timepoint 1 (B) night 1 of monitoring, timepoint 3

7.2.2.2 Monitoring seating data

Monitoring whilst sitting from P11 showed no pressure relieving activity during the monitoring period. The static postures are illustrated in Figure 7.8 and 7.9. As discussed in previous chapters, P11 has high level injury and low level of function. She had limited core control and upper limb control, therefore has difficulty performing pressure relieving movements.

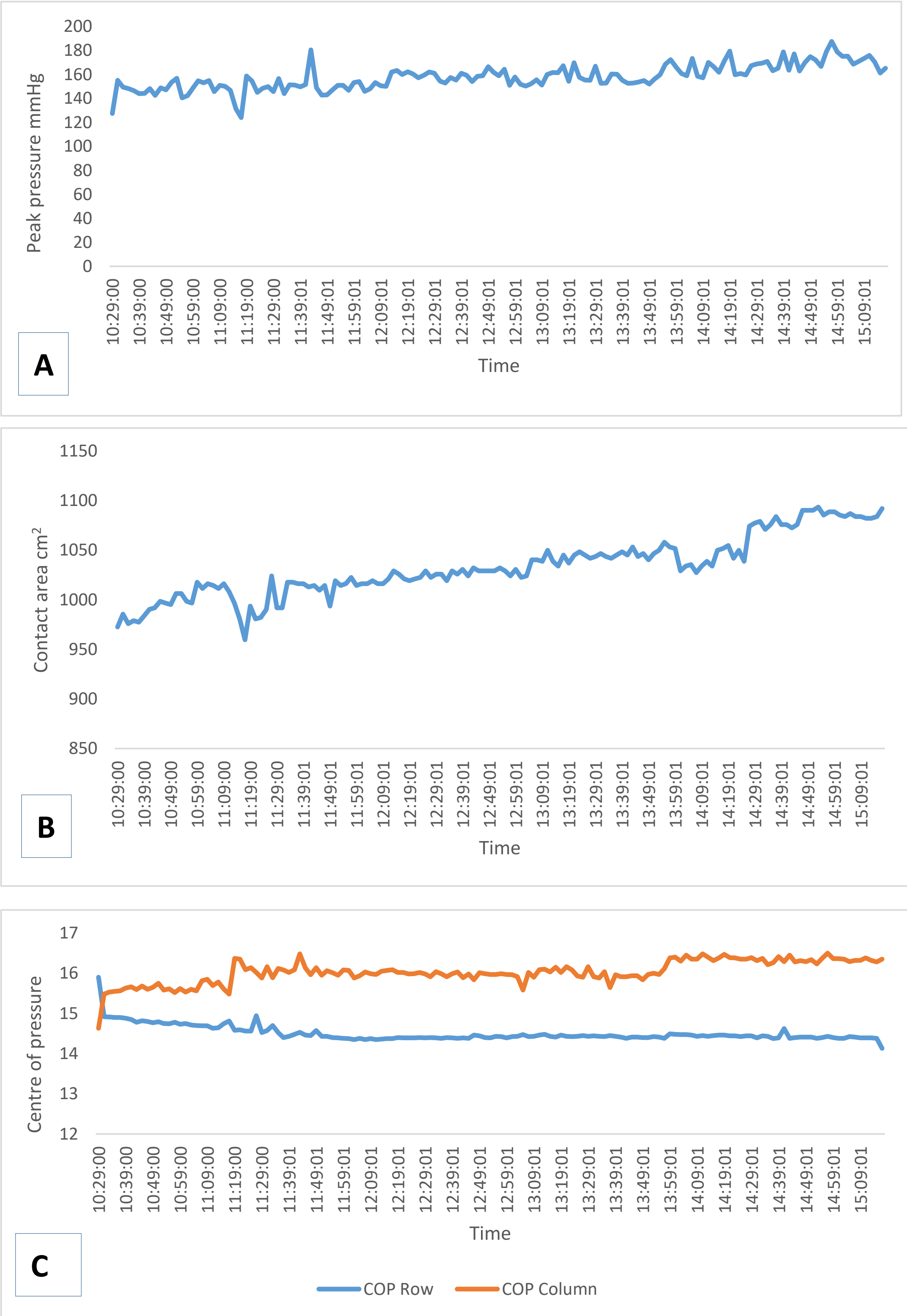
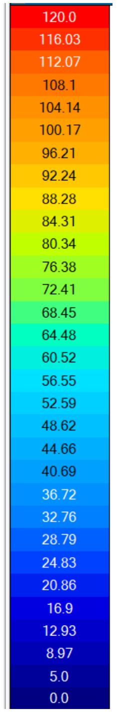


Figure 7.8: Temporal profiles of (A) peak pressure (B) contact area (C) centre of pressure, row (D) centre of pressure column for P11 on T3, day 1 of pressure monitoring on wheelchair cushion

Seating posture at 2 hourly intervals –day 1



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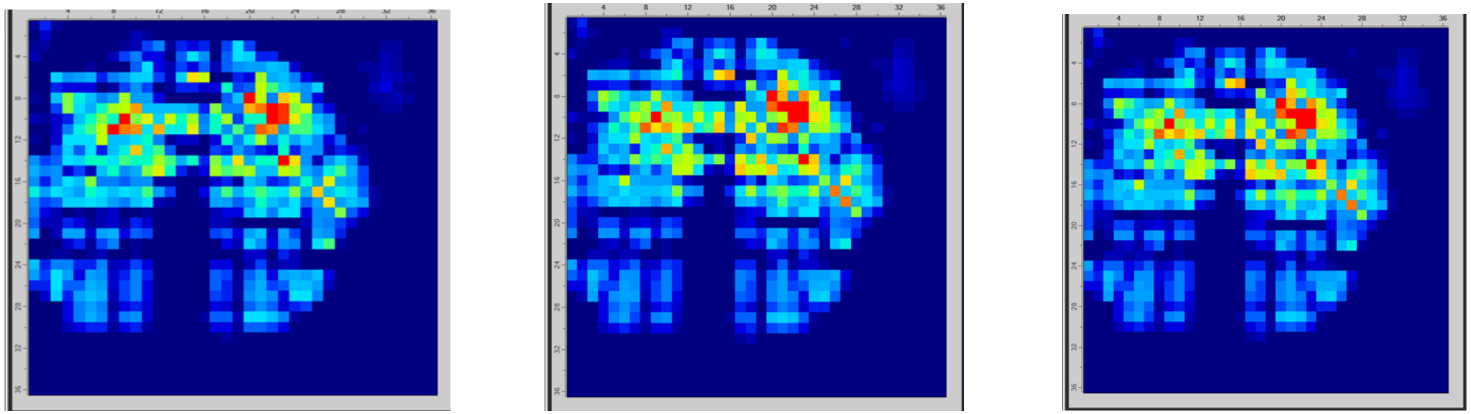


B **C** **D**

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
11:00	151	1012	14	15
13:00	152	1022	14	15
15:00	172	1079	14	16

Figure 7.9: Pressure scale ranging from 0 – 120 mmHg,Pressure distributions and corresponding pressure parameters for sitting postures at two hourly intervals (B) 11:00 (C) 13:00 and (D) 15:00 for P11, day 1 of monitoring, timepoint 3.

7.2.3 Participant 13

Participant 13 was injured at C5 level with an ASIA score of B. He was monitored in the community 32 weeks post discharge and 18 months post injury. He had been discharged to his home. As previously discussed P13 had a high level injury and low functional score. A care package was provided during the day to help with washing and dressing. To provide pressure relief overnight at home a lateral turning system was provided Toto Lateral Turning System (Frontier Medical Group, UK).

Skin assessment

P13 had a history of bed rest related to skin damage. Scar tissue was present in the sacrum and natal cleft. No skin damage was observed during time-point 3 monitoring.

Support surfaces and transfers

P13 was a full hoist transfer, with AO2. He used a foam mattress with a lateral turning system. He had an air cushion for his wheelchair

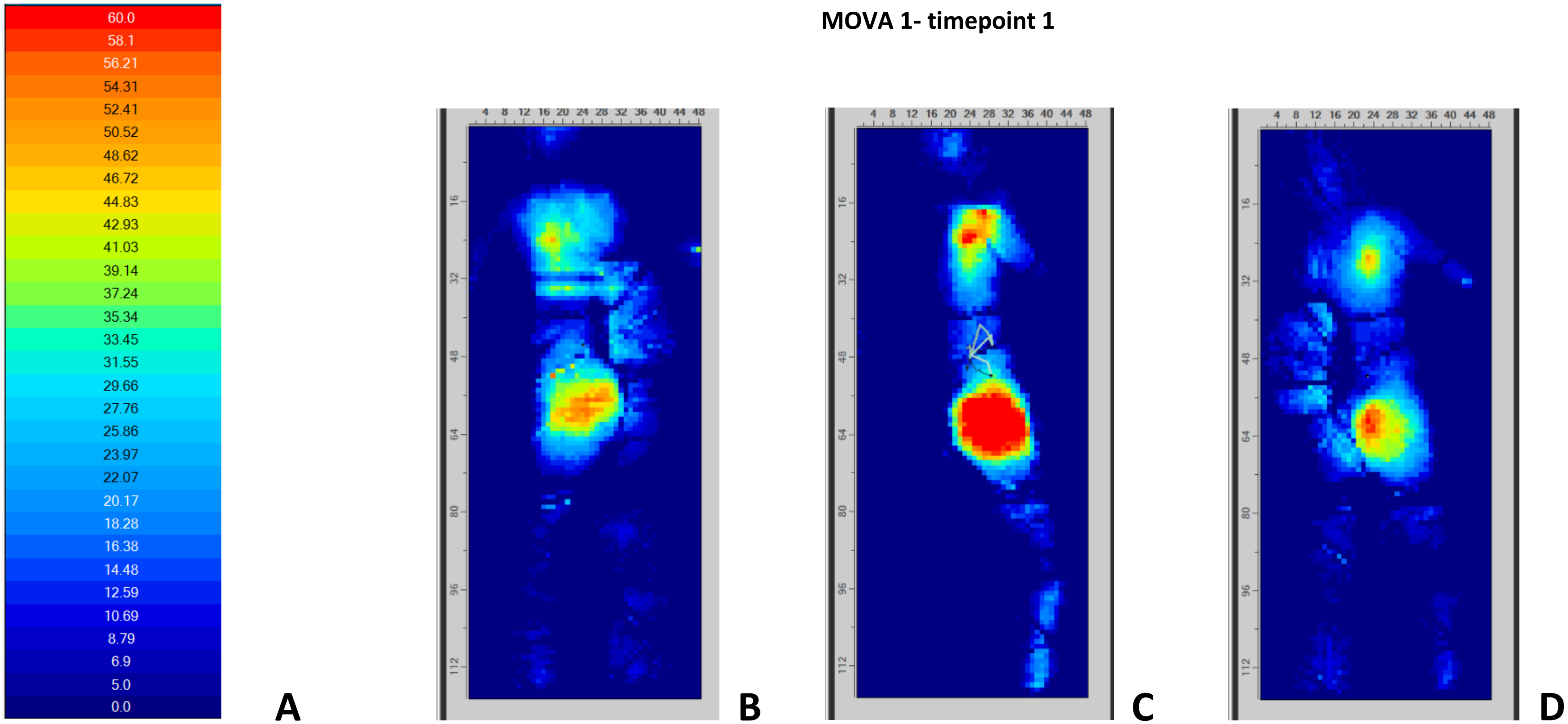
Table 7.8: Summary of movement behaviour of P13 on foam mattress and wheelchair cushion at time point 3.

Night	***Time monitoring started***	***Monitoring period on mattress (mins)***	***Number of MOVAs***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	19:02:55	1102	1	224	805
2	19:05:47	1039	1	201	835
Day	***Time monitoring started***	***Monitoring period on cushion (mins)***	***Number of MOVAs***	***Minimum time between MOVAs (mins)***	***Maximum time between MOVAs (mins)***
1	14:29:20	313	0	311	311

7.2.3.1 Monitoring lying data (night 1)

P13 was monitored for 18 hours and 22 minutes on night 1. In the manual tilts observed in timepoint 1 (Figure 7.10), there were clear changes in the spatial distribution during a 90 degree pelvic tilt. Here the COP changes by six rows corresponding to a 78mm translation across the support surface and clear change in the spatial distribution of pressure. By contrast, during the automated tilt, pressure distributions remained similar pre-and post-tilt, with only a small translation in the COP. Indeed, the sacral site remained the area of the highest pressures in both supine and tilted postures

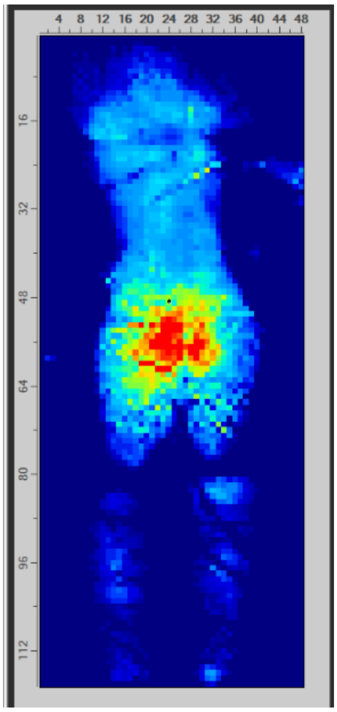
Figure 7.11.It is evident from the temporal profiles, that the lateral turning system provided limited offloading of the vulnerable sacral site. It can be observed by the change in the spatial distribution of pressures (Figure 7.11). Here peak pressures transition towards the side of the tilt, although high values (>50mmHg) remain in the sacrum. This is also demonstrated in the COP changes, where a single row (13mm) change is observed during the tilt.



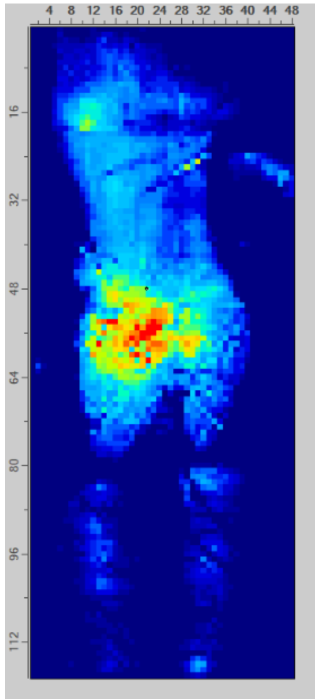
Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
03:06:01	57	4438	45	24
03:08:15	95	3127	51	28
03:26:07	62	4589	51	22

Figure 7.10: (A) Pressure scale ranging from 0 – 60mmHg. Pressure distributions and corresponding pressure parameters for P13 (B) right side lateral (C) left side lateral (D) left side lateral for MOVA 1

MOVA 1 – timepoint 3



A



B

Time	Peak Pressure (mmHg)	Contact Area (cm^2)	Centre of Pressure Row	Centre of Pressure Column
06:18:18	82	5733	48	24
06:33:18	86	6154	47	21

Figure 7.11: Pressure distributions and corresponding pressure parameters for p13 which depicts repositioning on lateral turning system from (A) Supine (B) Left side lateral for MOVA 1, night 1, timepoint 3

Due to the limited offloading during the tilts provided by the automated lateral turning system, this was not considered MOVAs. Therefore, there is only 1 MOVA during night 1 and night 2 of timepoint 3 monitoring, during a carer visit. This is demonstrated in Table 7.9 and Figure 7.12.

Table 7.9: Summary of movements P13, night 1 of monitoring, timepoint 3

MOVA	Maximum time between MOVA *(mins)*	Time started	Duration *(mins)*	Description
1	805	08:29:28	65	Left side lateral> supine
Transfer off bed	224	13:18:41		

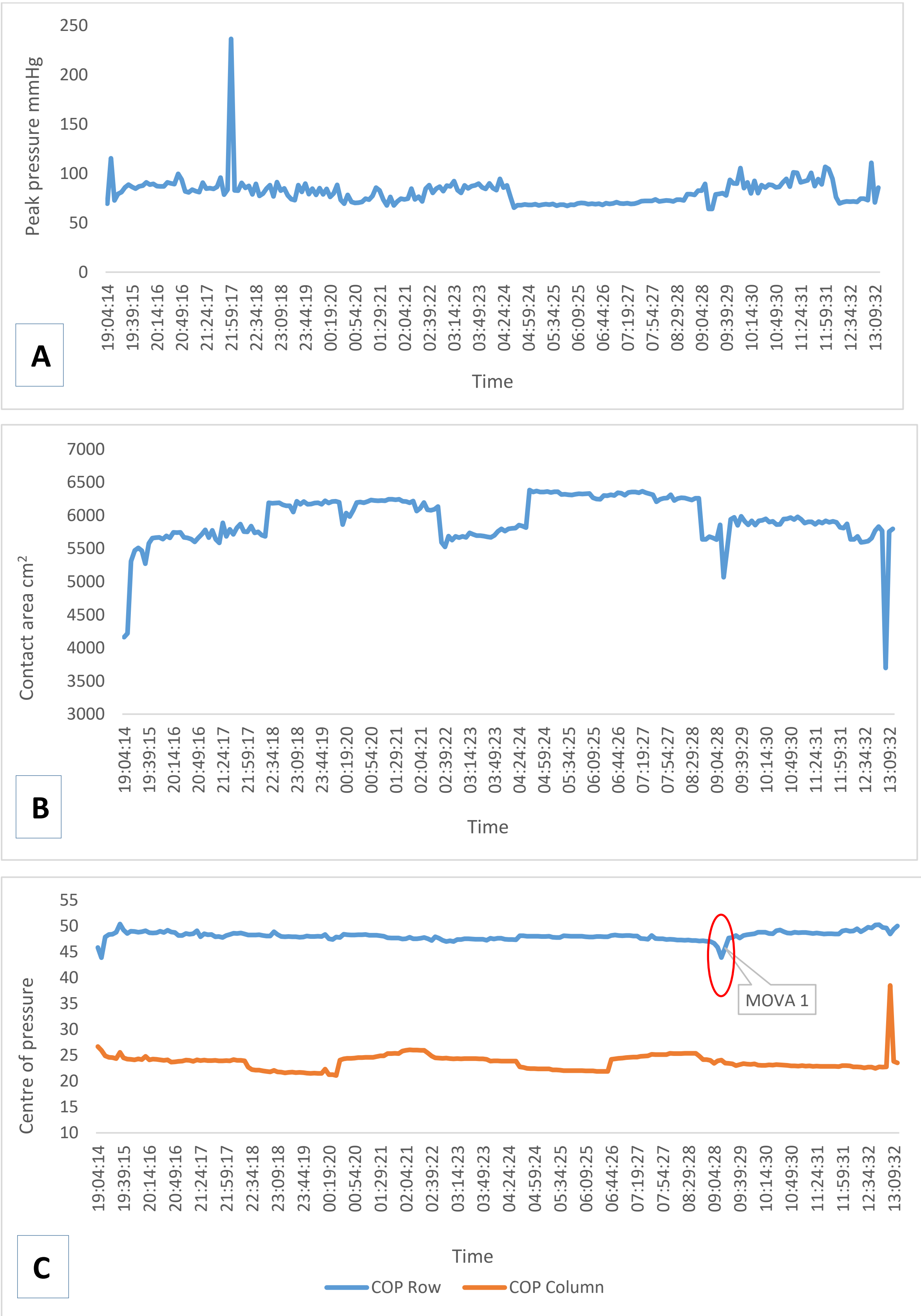


Figure 7.12: Temporal profiles of (A) Peak pressure (B) Contact Area (C) Centre of Pressure, row (D) centre of pressure, column for P13 at timepoint 3, night 1 of pressure monitoring on mattress and lateral turning system

7.2.3.2 Monitoring seating data

Monitoring whilst sitting showed no pressure relieving activity over the 5 hour period of monitoring. As previously discussed, P13 has a high-level injury and a low level of function, therefore limited capacity to perform pressure relieving movements. Although perturbations in contact area and centre of pressure can be seen in Figure 7.13. Upon visual inspection of the monitoring, this was repositioning of the leg, or created by the air-based wheelchair cushion. Pressure distributions at 2 hourly intervals are shown in Figure 7.14 and demonstrate the lack of repositioning over the monitoring period.

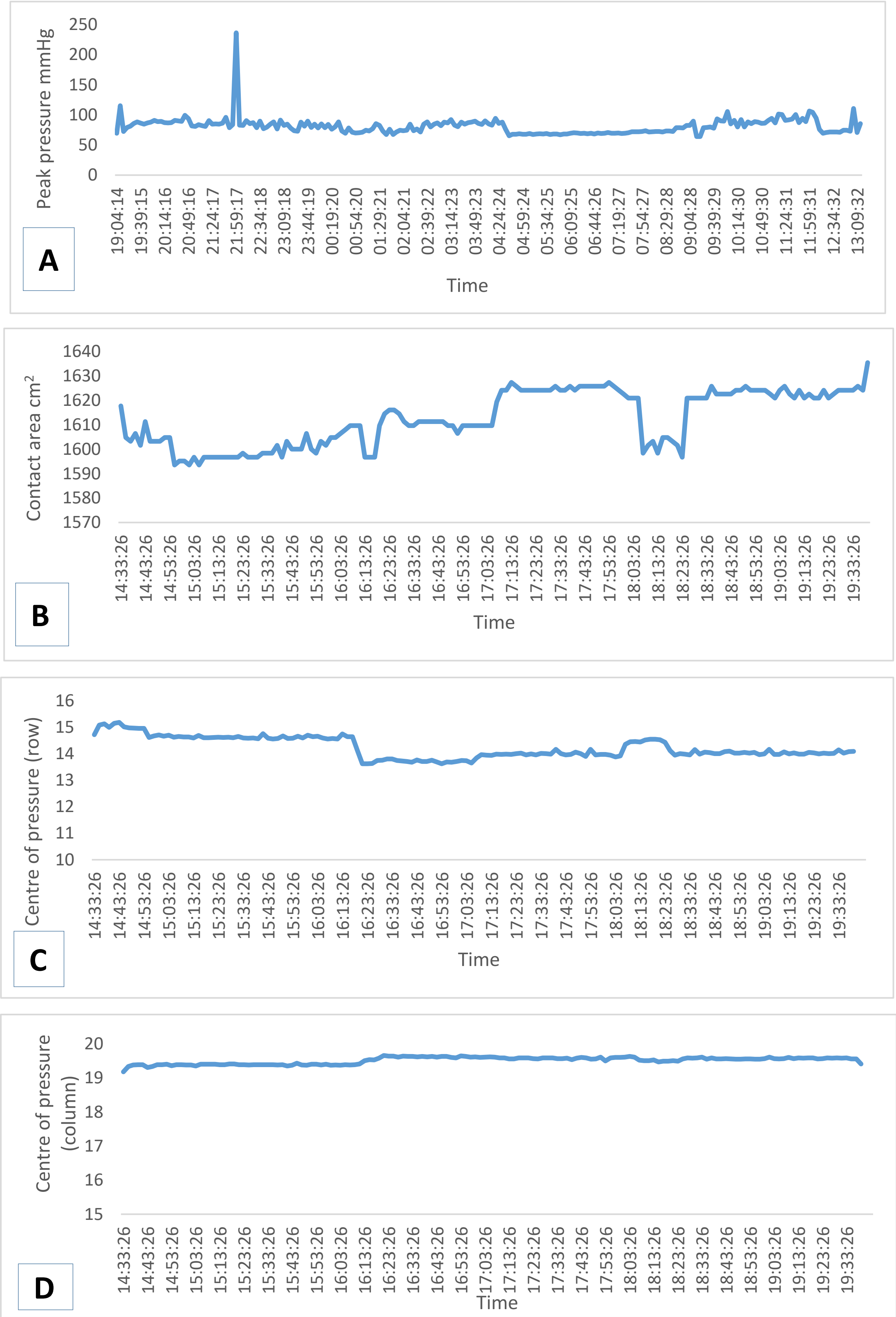
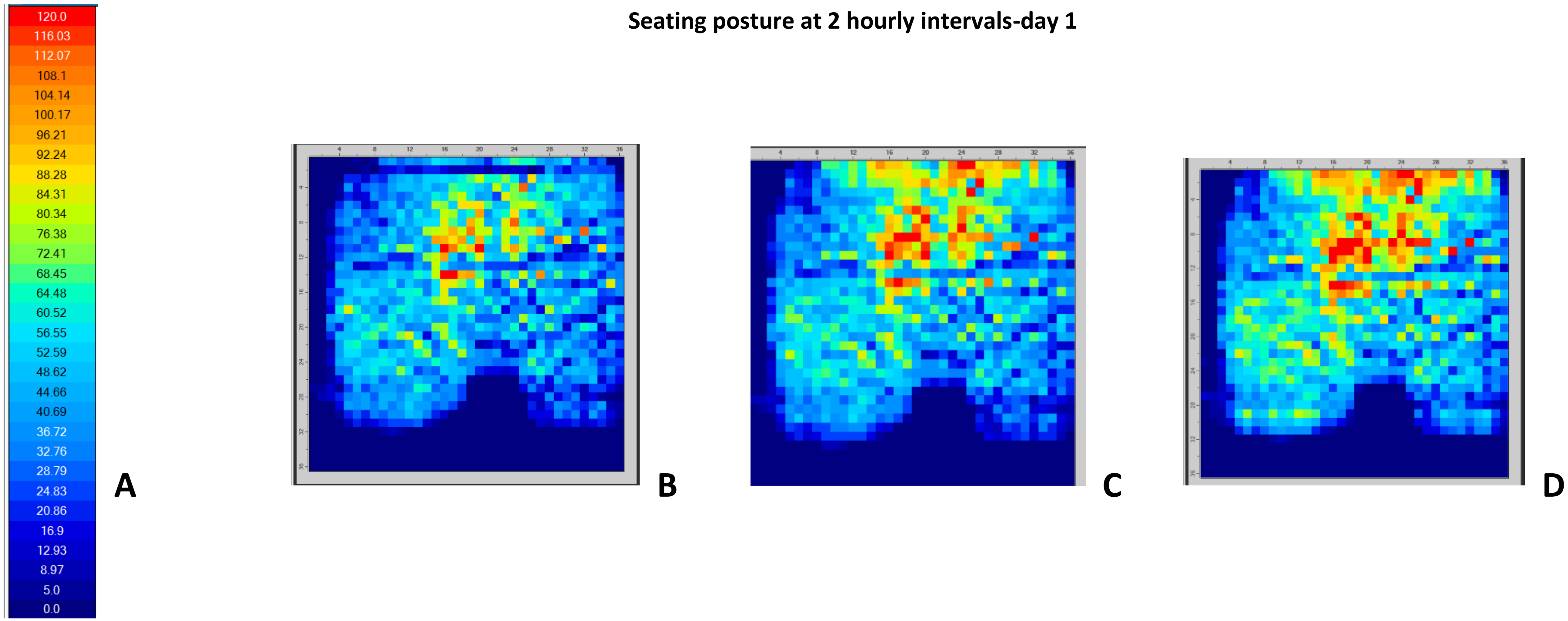


Figure 7.13: Temporal profiles of (a) Peak pressure (b) Contact Area (c) Centre of Pressure, row (d) centre of pressure column for P13 at timepoint 3, day 1 of pressure monitoring on wheelchair cushion



Time	Peak Pressure (mmHg)	Contact Area (cm$^{2)}$	Centre of Pressure Row	Centre of Pressure Column
15:00	149	1596	14	19
17:00	145	1609	13	19
19:00	152	1622	14	19

Figure 7.14: (A) Pressure scale ranging from 0 – 120 mmHg. Pressure distributions and corresponding pressure parameters for sitting postures at two hourly intervals (B) 15:00 (C) 17:00 (D) 19:00, P13, day 1, timepoint 3

7.3 Analysis of movement profiles in community settings

This section will provide a comprehensive analysis for all participants who were monitored in the community setting. As in Chapter 5, two parameters will be used, namely the maximum time between MOVAs and average number of MOVAs per hour. Data obtained from P5 whilst sitting was not included in the analysis, as her mobility allowed for a different pattern of movement, not observed in other participants. Due to COVID 19 restrictions on patient access (Table 5.3), it was not possible to obtain seating data from P10 and P12. Both P1 and P13 used a lateral turning system overnight. However only manual turns were included in this analysis due to the limited offloading achieved, which was observed earlier in this Chapter (Figure 7.11).

The associations between movement patterns and patient demographics were compared, consistent to that of the analysis in Chapter 5 (Section 5.3). To review briefly, two patient characteristics was considered, namely, the level of injury and ASIA score. A summary of the patients included in the timepoint 3 assessment is provided in Table 7.10.

Table 7.10: Characteristics of patients included in timepoint 3.

Participant	Level of injury	ASIA
P11	C4	B
P13	C5	B
P14	C8	B
P1	T6	A
P4	T10	A
P15	T11	A
P10	T11	A
P12	L2	B
P8	T4	D
P5	T11	D

7.3.1 Movements in the lying position

Figure 7.15, which represents average number of MOVA per hour for each category of spinal injury level, during the lying monitoring period. The data reveals a similar trend to that which was observed in timepoint 1 (Figure 5.29). It is evident that persons with spinal cord injury (PWSCI) with higher injuries, namely those in the cervical region (median=0.08, range 0.05- 0.23) and upper thoracic (median=0.04, range 0-0.07) moved less frequently in comparison to PWSCI with injures T7 and below (median=0.45, range 0.21-0.72).The corresponding maximum intervals between MOVA (Figure 7.16) were also higher for PWSCI with injuries in the cervical region (median= 10.6, range 4.3-13.9 hours) and above T6 (median= 11.4, range 10.0-12.9) than those with injuries T7 and below (median= 5.1, range 3.2-7.7).

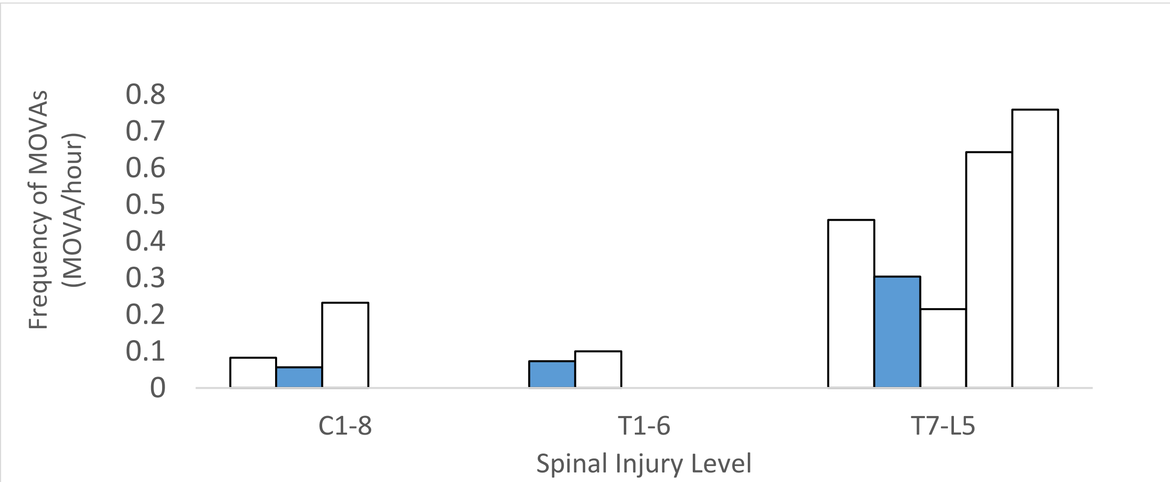


Figure 7.15: Clinical estimation of average number of MOVAs in lying position with respect to spinal level of injury of the participants at timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

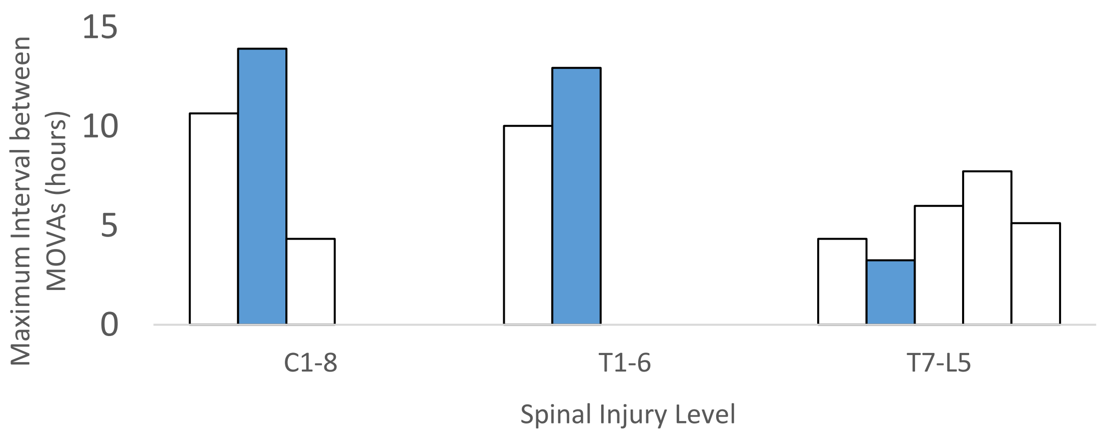


Figure 7.16: The clinical estimation of maximum interval between MOVAs in lying position with respect to level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

No notable trends were observed in the lying movement parameters from timepoint 3 when patients were grouped by ASIA score. Indeed, it is interesting that notable trends found in time point 1 were not observed at timepoint 3 when patients were discharged to the community setting. Average number of MOVAs per hour ranged between 0-0.64 across all participants, with ASIA A median MOVA frequency of 0.34 (range 0-0.64 MOVA/hour) and ASIA D median MOVA frequency of 0.19 (range 0.07-0.3 MOVA/hour). This is represented in Figure 7.17. Maximum times between MOVAs was similar for all three ASIA categories (Figure 7.18). Namely, ASIA A (median= 6.8, range 4.3-12.9 hours), ASIA B (median=7.8, range 4.3-12.9) and ASIA D (median=6.6, range 3.2-10.0).

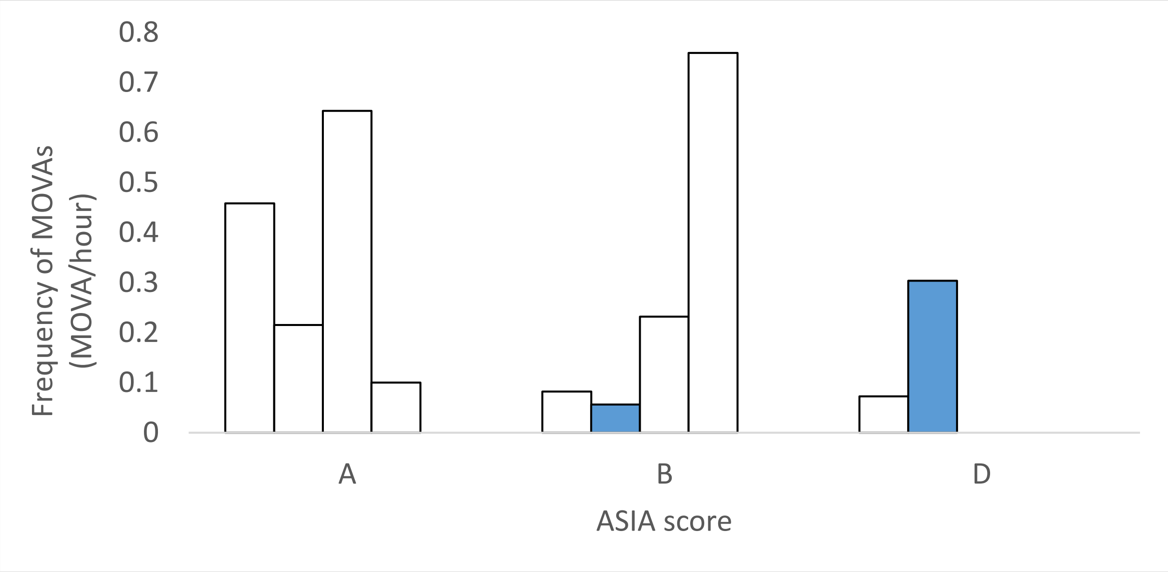


Figure 7.17: Clinical estimation of average number of MOVAs in lying position with respect to ASIA score of the participants at timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

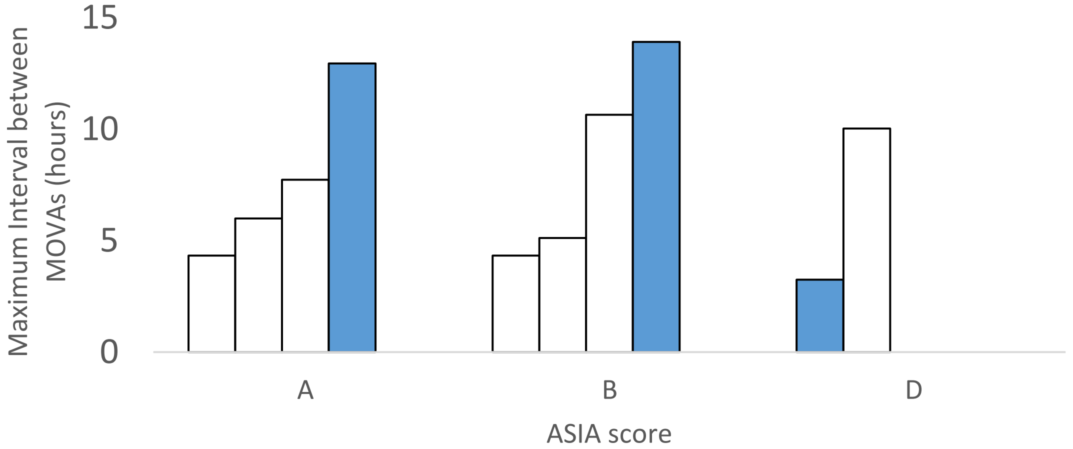


Figure 7.18: The clinical estimation of maximum interval between MOVAs in lying position with respect to ASIA score, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

It is of note that both P5 and P12 had longer Maximum time between MOVAs, with over 12 hours of static posture.

7.3.2 Movements in the sitting position

The analysis did not produce any notable trends in the timepoint 3 sitting data. This is in contrast to the trends between spinal level of injury and MOVAs on wheelchair cushion was observed in timepoint 1.

When discussing spinal level of injury and frequency of MOVAs it is evident that medians differed between groups. However, closer examination of the ranges reveal distinct overlapping, therefore definitive differences between spinal levels were not observed. The analysis reveals a high degree of inter-subject variability for each spinal level, namely cervical (median=0.00, range 0.00-1.54), T6 and above (median=0.26, range 0.19-0.33) and T7 and below (median=0.47, range 0.30-0.47). It is also evident that the highest and lowest number of MOVAs is attributed to a participant injured in the cervical region. There is also no easily identifiable trend demonstrated in the maximum times between MOVAs, with significant overlap between the values in each group. It is also relevant the shortest time between MOVA is attributed to a participant with an injury in the cervical region.

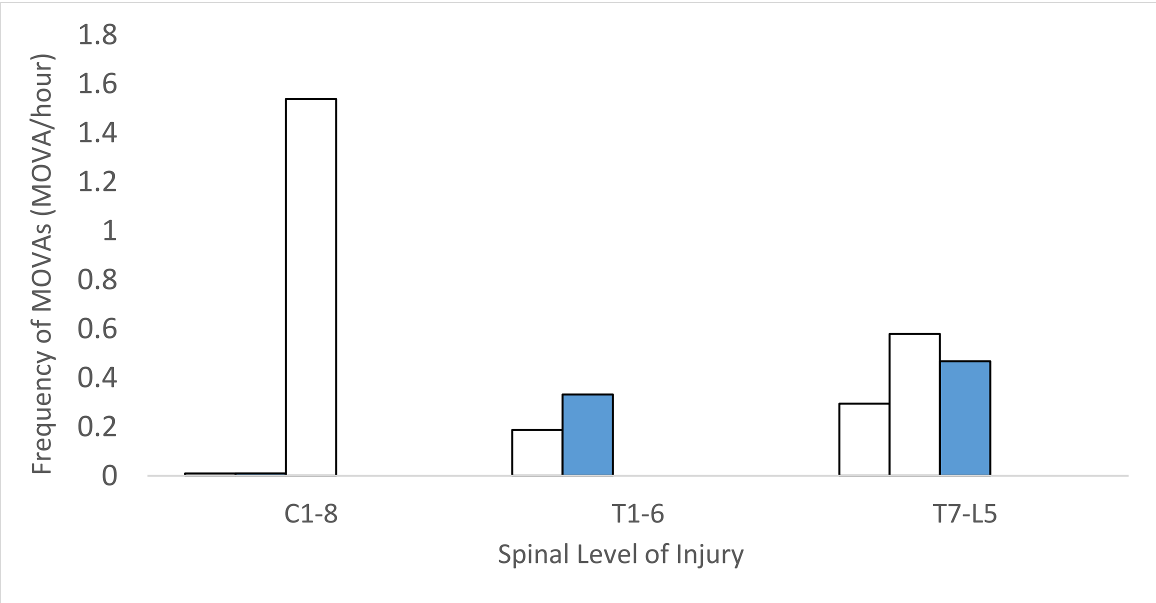


Figure 7.19: The clinical estimation of Frequency of MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

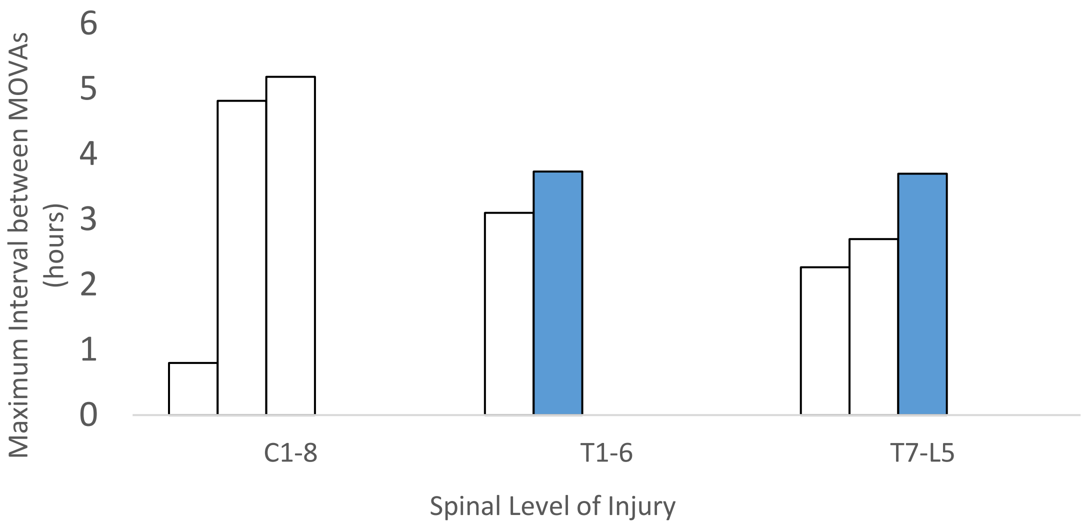


Figure 7.20: The clinical estimation of maximum interval between MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

Indeed, the results relating to seating data revealed no distinct differences between movement parameters and ASIA score (Figure 7.21 & 7.22). With the lowest number of MOVAs attributed participant in the with an injury ASIA B category (median=0.00, range 0-01.54). The highest and lowest Maximum interval between MOVAs was also attributed to ASIA B category (median=4.8, range 0-5.1). Overall, the high degree of inter-subject variability limits any observations of differences between groups.

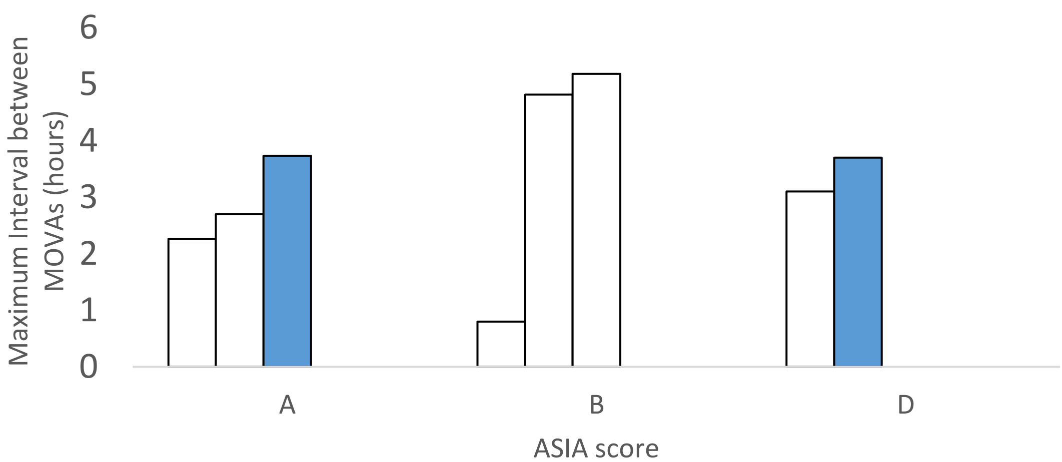


Figure 7.21: The clinical estimation of maximum interval between MOVAs in sitting position with respect to ASIA score, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

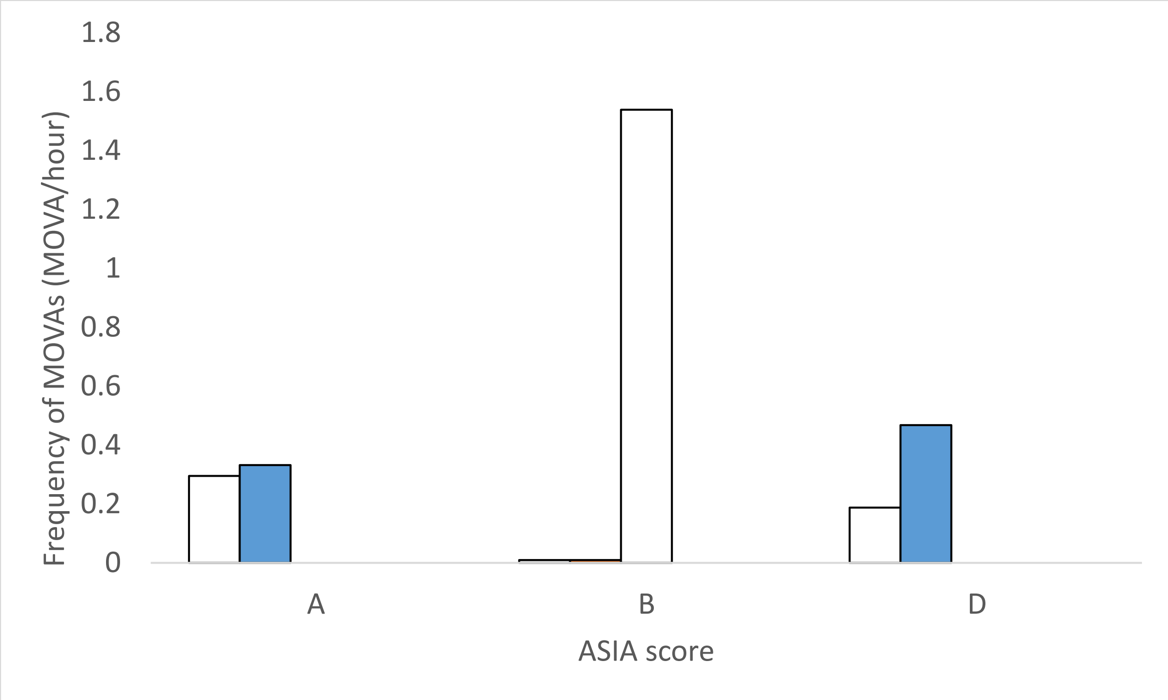


Figure 7.22: The clinical estimation of maximum interval between MOVAs in sitting position with respect to spinal level of injury, timepoint 3. Those who were observed to have skin damage during inpatient rehabilitation are denoted in solid blue bars.

7.4 Discussion

The present chapter has identified movement patterns in PWSCI following discharge to their community residence. The location in which individuals transitioned to following their inpatient stay varied, including private homes, nursing home and a rehabilitation centre. Following discharge there were different strategies for pressure ulcer (PU) prevention, for example, self-turning, manual turns and automated lateral turning system with varying degrees of carer support. Indeed, varying levels of clinical knowledge and standards of care can be an issue when seen predominantly in primary (community) care services (Milligan et al. 2020). This could account for the range of movement parameters observed in the present study, in addition to some distinct changes from the observations made during the inpatient period (Chapter 5). Indeed, some notable trends did remain from inpatient monitoring, for example the relationship between MOVAs and the level of spinal cord injury in the lying position (Figure 7.15). However, many of the demographic factors associated with movement patterns were no longer evident, demonstrating distinct changes in the community setting (Table 7.11).

Table 7.11: Summary of median and range values, corresponding to spinal injury characteristic . Notable trends are highlighted in yellow

		Frequency of MOVAs		Maximum interval between MOVAs	
Spinal Injury Characteristic	Support Surface	Median	Range	Median	Range
ASIA A	Mattress	0.34	0-0.64	6.8	4.3-12.95
ASIA B	Mattress	0.16	0.06-0.75	7.8	4.3-13.91
ASIA D	Mattress	0.19	0.07-0.30	6.6	3.25-10.0
Cervical	**Mattress**	**0.08**	**0.05-0.23**	**10.6**	**4.3-13.9**
T6 and above	**Mattress**	**0.04**	**0-0.07**	**11.4**	**10.2-12.9**
T7 and below	**Mattress**	**0.46**	**0.2-0.75**	**5.1**	**3.2-7.7**
ASIA A	Wheelchair cushion	0.33	0.30-0.58	2.7	2.2-3.7
ASIA B	Wheelchair cushion	0.00	0.00-1.54	4.8	0.8-5.1
ASIA D	Wheelchair cushion	0.33	0.19-0.47	3.4	3.1-3.7
Cervical	Wheelchair cushion	0.00	0.00-1.54	4.8	0.8-4.1
T6 and above	Wheelchair cushion	0.26	0.19-0.33	3.4	3.1-3.7
T7 and below	Wheelchair cushion	0.47	0.30-0.58	2.7	2.2-3.7

It was of note that many of the support surface (mattress systems) changed between inpatient and community settings. In addition, there was the introduction of turning support systems (ToTo) for two patients. Indeed, for some individuals e.g. P11, they were provided a high specification air mattress. The corresponding interface pressure values did not improve (Figure 7.7) and this was associated with a very low number of MOVAs (1 MOVA over a ~10 hour night period). In this instance, there could have been an over reliance on the support surface and insufficient turning at night. The selection of support surface may have been dependent on the discharge location of the PWSCI, where each community trust/care facility will have a range of options. Indeed, this process should be in collaboration with the patients, where some individuals do not like alternating pressure aire mattresses (APAM), with individuals reporting issues with feeling unsafe and disturbances from the pumps (Hopkins et al. 2006b; Shi et al. 2018). There are also some reports that APAMs restrict movement and independence, exacerbate existing balance/mobility problems and leave patients in need of extra care (i.e. help in repositioning) (Nixon et al. 2019a).

Although the community data revealed a notable trend between SCI level and frequency of MOVAs, in the lying position, two distinct clusters of patients can be observed (Figure 7.15). Indeed, those with a neurological level of injury above T7 had a low number of movements. By contrast, those with a neurological below T7 had a higher frequency of movements during the monitoring period.

This can, in part, be explained by the recovery characteristics of PWSCI, where individuals with lower level injuries can gain more functional independence and movement with recovering motor and sensory function (Nas et al. 2015). Indeed, P5 is an example of a PWSCI who had recovered a significant level sensation and function, and demonstrated a different pattern of movement during the community monitoring. This involved regular standing/walking intervals and repositioning. By contrast, P13 is an example of a PWSCI with a high level injury and low level of function, who was provided with a lateral turning system, as opposed to manual turning overnight.

The Toto® Lateral Turning System (Frontier Medical Group, Blackwood, Wales, UK) was shown to provide minimal offloading of key anatomical areas e.g. sacrum (Figure 7.11), and therefore the corresponding movements were not defined as MOVAs. It was evident the lateral turning system had minimal effect on the peak pressures, pressure distribution or COP. This was also observed in previous studies evaluating automatic tilting systems (Woodhouse et al. 2015). Although lab-based studies did demonstrate some physiological effects on local tissues, indicative that the systems may have partially offload vulnerable bony prominences i.e. sacrum. The degree by which individuals are tilted may play a significant role in the system's ability to effect local tissues, for example it has been demonstrated that a 45 degree tilt has a significant effect on local tissue strains over vulnerable bony prominences (Oomens et al. 2016). Other studies have also shown that depending on the degree of tilt there can be significant changes in interface pressure, although this study relied on peak pressure and mean pressure values, which result in a large amount of data redundancy and neglect the spatial distribution of pressure values critical to informing pressure ulcer risk (Do et al. 2016). It is of note that previous studies have identified that the Toto system is well-tolerated by patients in community settings (Lahmann 2021). During the present study the maximum time between MOVAs increased for P1 and P13 who were provided the Toto. It can be suggested that changes to environment, support surfaces and routine can affect frequency of movement, with reliance on tilting systems potentially limiting key interventions to support offloading in bed.

It can also be suggested there are less audible and visual disturbances in the home environment, as opposed to a shared bay in a hospital ward, which could improve sleep. Indeed, shared bays in hospital wards create a difficult sleep environment. It has been suggested that sleep disturbances can last up to 12 months after critical illness, exacerbated by both pre-hospital and in-hospital factors, although this is likely to improve over time (Altman et al. 2017). Some of the reductions in movement observed overnight could result in a higher risk of pressure ulcer. However, there is a balance to ensuring sleep quality and pressure ulcer prevention over-night (Sharp et al. 2019). PWSCI balance the risk of developing PUs with the need for comfort and function, with a personalised multidisciplinary approach advised for best care. Prevention should also be formed by shared decision making between the individual and their healthcare professional. Jackson et al. (2010) led a qualitative research initiative to understand the lifestyle principles that are relevant in pressure ulcer development, in particular suggesting that patients with SCI have at least eight lifestyle principles that govern their risk:

I. Perpetual danger (SCI patients are constantly at risk for pressure ulcers).

II. Change/disruption in routine

III. Decay in prevention behaviours

IV. Lifestyle risk ratio

V. Individualization

VI. Simultaneous presence of awareness/motivation

VII. Lifestyle trade-off

VIII. Access to needed care, services and support

Since lifestyle factors can be vastly different from patient to patient, the risk profile of patients becomes an individualized assessment, with likely individualized prevention strategies in need of definition and implementation. The use of continuous pressure monitoring (CPM) and IPUPP interventions could form the basis of shared working between patients and healthcare workers, where monitoring data can be used to assess risk, identify trends that patients can also observe and derive common goals for pressure ulcer prevention strategies. This is particularly important in the community where there is limited access to healthcare resources and monitoring is critical to avoid PUs and associated hospitalisations.

7.5 Summary of key findings

- Results in the community settings, differed from those in the inpatient setting
- Some trends evident at timepoint 1, for example MOVA and level of spinal injury in the lying position, did remain at timepoint 3.
- However, other injury characteristics associated with movement patterns at timepoint 1 were less evident at timepoint 3 in the different environmental settings.
- The high degree of inter-subject variability limits any observations of between group differences in the sitting position. This could have resulted from the different environments in which patients were assessed in the community.
- There may be an overreliance on high specification support surfaces and automated turning systems in the community setting.
- Interface pressure values corresponding to these individuals did not reveal significant offloading of vulnerable tissue sites.

Chapter 8 Discussion

This chapter will begin by discussing the success of the study in terms of original aims and objectives detailed in Chapter 4. Limitations encountered over the study period will then be described. The third section outlines the achievements of this study in terms of novel work and advancement of scientific understanding in the field of pressure ulcer (PU) prevention for individuals with spinal cord injury (SCI). The final section will discuss how the current thesis can inform future work in PU prevention in a wider context.

8.1 Achievements in relation to original aims and objectives

The following paragraphs will detail how this novel research has successfully answered research questions 1 and 2, the global aim and aim 1 set-out in section 4.1 and 4.2.

The XSENSOR Foresite system successfully allowed for continuous pressure monitoring (CPM) of recruited SCI participants on a range of prescribed mattresses in the lying position. This was achieved in both the inpatient and community locations for between one to four nights. In addition, the XSENSOR SS provided up to 9 hours of pressure monitoring in the sitting position in both settings. The use of an external battery and adapted backpack allowed the CPM system to be used to monitor participants in a range of seating environments (Figure 4.2). Although a few previous studies have reported the use of CPM, they have been limited to either monitoring patients in sitting or lying positions. For example, Behrendt et al. (2014) and Pickham et al. (2018) examined the use of CPM in a lying position in an ITU setting. By contrast, Moreau-Gaudry et al. (2018) and Hubli et al. (2021) examined CPM in the sitting position, in both research and community settings. Accordingly, the present thesis represents the first to examine pressure profiles in both lying and sitting postures for a group of SCI individuals, in the form of a longitudinal design which incorporated both hospital and community settings. In addition, the translation of this pressure-related data to movement behaviour over the extensive monitoring period represents a novel aspect of the present work.

The commercial CPM software (Pro V8) provided both visual and statistical feedback, as demonstrated in Chapters 5, 6 and 7. Visual feedback was in the form of body-maps representing spatial pressure distribution e.g. (Figure 5.2). From an array of sensor values a series of well-established pressure parameters could be extracted. These include peak pressures, contact area and centre of pressure (COP), the latter two of which have been demonstrated to be effective in monitoring mobility in lying postures (Caggiari et al. 2019). Therefore, a comprehensive analysis of the data has involved identifying associated changes in these key parameters and relating them to pressure-relieving movements over the extended monitoring periods, in conjunction with visual inspection of the pressure mapping images. As an example, a change in COP with respect to the rows of the pressure mat (Figure 5.1), indicated movement of the lying participant from the left or right side, confirmed through a distinct change in the spatial distribution of the pressures. Manual turns often resulted in a decrease in contact area (Figure 5.11) with the participant lying on their side, with distributions of peak pressures corresponding to the greater trochanter and shoulder sites. This approach relating pressure monitoring as a surrogate for estimating the temporal profile of movement in both lying and sitting postures, represent a major advancement in the use of CPM technologies in the clinical environment. Indeed, the current software associated with the CPM system relies on manual nursing/carer notification of movements during monitoring, with limited use of retrospective analysis of data (Behrendt et al. 2014).

The CPM systems are sensitive to pressure-related parameters, which could be translated to both the frequency of movement and the magnitudes of the defined movements. As the temporal profiles of COP were estimated, the magnitude of movements at two distinct timepoints could be compared. This was particularly relevant when examining, for example, the behaviour of P13 in a lying position, who was manually turned by healthcare workers in the hospital at timepoint 1, but dependent on a lateral turning system in the community setting at timepoint 3. It was possible to identify that the lateral turning system did not result in the same magnitude of movements, and as a result off-loading, as was apparent when he was subjected to manual turning (Figure 7.6). This was clearly demonstrated by the decreased movement of the COP along the row of sensors in the pressure mat when the participant was being turned on the lateral turning system (Figure 7.7). These findings align with an earlier study from the host lab which compared the performance of an automated tilting mattress compared with conventional manual turns (Woodhouse et al. 2015). These authors demonstrated that although an automated tilting mattress offers the ability to periodically reposition vulnerable individuals, it produces tilt angles at the sternum and the pelvis which were significantly less than those associated with the manual tilt. Of note in the present work was the limited change in pressure distribution, with the sacral region remaining loaded throughout the automated tilting (Figure 7.7). By contrast, during manual turning by nurses, there was a clear indication of sacral off-loading (Figure 7.6).

By using an external battery and adapted backpack, it was possible to collect up to 9 hours of detailed pressure-related sitting data for those who were mobile in their wheelchair. These data included estimates of peak pressures, contact area, centre of pressures derived from body maps of spatial pressure distribution, which could be used for visual feedback. The approach also enabled the participants to perform their usual functional routines, without frequent interruptions to permit recharge of the Foresite SS system. This enabled any differences in movement patterns in sitting to be related to individual spinal levels and severity of injury in persons with spinal cord injury (PWSCI), as presented in Chapters 5-7.

Due to the multiple pressure parameters which could be extracted from the output of the CPM system, and the repeated measures undertaken in this study, it was possible to examine the performance of different support surfaces. This was particularly relevant when examining the pressure-related data derived from P11. She was on lying on a foam mattress during timepoint 1, but had been prescribed an pressure alternating air mattress (APAM) for use in the community at timepoint 3. It was evident that this change of mattress resulted in a decrease in the frequency of movements, although the peak pressures remained similar over a period of one night (Figure 7.12). It can be suggested there was an overreliance on the APAM for pressure relief. The perception that this automated system would reduce overall pressures, resulted in extended intervals between manual turns. For example, at timepoint 1 for P11 the maximum time between movement to offload vulnerable areas (MOVA) was 455 minutes, which increased to 585 minutes at timepoint 3.

Previous studies have reported both detection in the frequency of movement and distinguishing between weight shifts and in seat movement. For example, Sprigle et al. (2019) used a seating system incorporating four 50mm interlinked force sensors. This compares with the present study employing a seating system with 1296 sensors, with a spatial resolution of 12.7mm. Therefore, this represents a first study to provide a detailed analysis of both spatial distribution of pressures and temporal profile of parameters linked to movement. Both features are essential to accurately detect both the magnitude and frequency of movement, in addition to the evaluation of the effects of posture on pressure profiles. However, the increased resolution of sensors, inevitably results in an exceptionally large data set during continuous monitoring. This motivated the development of an algorithm to streamline data processing, as discussed in Chapter 5, for realistic use in a clinical setting.

This study has established two movement parameters that can be derived from CPM using both clinical observation and computational algorithm. Average number of MOVAs per hour and Maximum time between MOVAs are robust movement-related parameters that indicate both the frequency and quality of movements, specifically in terms of offloading pressure from vulnerable tissues areas.

The following paragraphs detail how this research successfully answers research question 3, the global aim and aim 2 set out in sections 4.1 and 4.2.

Despite the premature discharge of many of the cohort and environmental changes associated with the COVID pandemic, four patients were monitored at two timepoints in the hospital, which were separated by the introduction of a customized individualized pressure ulcer prevention plan (IPUPP). As detailed in Chapter 6, results indicated that the most improved pressure relieving behaviour, in terms of frequency of movement, was apparent in those participants who presented with a low level of function and had previous experiences with bed rest due to skin-related problems, e.g. P1 and P9 (Table 6.2). The interviews revealed that these participants also represented those who could coherently explain the advantages of the IPUPP to manage skin health. By contrast, the two participants with no prior experience of bed rest paid limited attention to the recommendations and potential benefits in their specific IPUPPs. This is exemplified in the response by P4 when asked what the advantages of the IPUPP could be, he replied "I wasn't aware of any disadvantages or advantages really". When asked if the there was any carer who supported him in carrying out the IPUPP he responded with "I've not asked anybody around so nobody's shown any interest in what I'm doing or anything like that so no I don't think there is anything there that could happen there". These comments clearly highlight the importance of individual self-motivation and engagement with a MDT team if the introduction of an IPUPP is to provide a positive contribution to the skin health of the individual.

These observations suggested that prior experience of discomfort during bed rest provided a major motivation for adhering to the IPUPP in taking an active role in maintaining skin health. Indeed, it has been reported that pain and/or discomfort were factors in adherence to a pressure ulcer prevention plan (Ledger et al. 2020). This recent review paper also suggested that it would be beneficial to investigate interventions that could be targeted at those who are at risk of PUs, but have not yet acquired a PU, such as PWSCI undergoing early stages of rehabilitation. In this respect, the combination of biofeedback and interviews provided a more comprehensive understanding of how the IPUPP was received, and the importance of motivational strategies to engage with skin health. A recent scoping review by Huter et al. (2020) also identified the benefits of a mixed methods process when investigating the introduction of new technologies in healthcare. The authors suggested that such innovations have complex effects on healthcare processes, which are only captured when this complexity is accounted for in the adopted methodology. In the current work, the mixed methods process certainly provided further insight in both the level of engagement and motivations of the participants.

The following paragraphs will demonstrate how this research answers research question 4 and aim 3.

Investigation of retrospective PU data from a specialised UK SCI Centre, as detailed in Chapter 3, revealed that PUs were most frequently present either on-admission or during phase 3 of functional rehabilitation (Figure 3.1). This corresponded to when PWSCI were mobilised in their wheelchairs for four hours or more, where individuals are given more independence to manage their own risk of PUs. It was also possible obtain data with reference to PUs present in the community, via the community liaison nursing service. This revealed that there was a high prevalence of stage 3 or 4 PUs in the patients discharged from specialist SCI units (Figure 3.5), with chronic wounds being a significant challenge for both patients and healthcare providers. This provided a focus for the prospective study presented in the current work. Accordingly, the study design was established where CPM was implemented in a time series of data collections, starting in phase 3 of their inpatient rehabilitation and extending to when individuals were transferred into the community. It is of note, that previous studies have not included the transition from hospital to community settings, which is clearly an important stage for the individual PWSCI (Gunningberg et al. 2017; Pickham et al. 2018; Hubli et al. 2021). Repeated monitoring of the same SCI participant in different settings enabled an in-depth analysis on the impact of both time since injury and the environment on pressure relieving activity supported by both quantitative monitoring data and interviews.

8.2 Limitations

Due to COVID 19 pandemic, the original study design of repeated measurements over the cohort in the hospital setting proved impossible to achieve. In order to increase capacity within the Major Trauma Centre (MTC) for treating COVID-19 patients, there was an accelerated discharge process into the community of SCI patients who were in the functional rehabilitation phase. This also enabled PWSCI waiting in acute hospital beds to transfer to functional rehabilitation sooner, and free extra beds in the acute hospital. It was therefore only possible to monitor a small number of patients (n=4) at two timepoints, while in the rehabilitation phase within the hospital setting. The pandemic also influenced the potential achievements of the monitoring capacity in the community. Indeed data collection was suspended while strict lockdown measures were operational in the community. Nonetheless, with continued support and enthusiasm from managers at the Salisbury NHS Foundation Trust, and with the appropriate safety precautions in place, it was possible to monitor a significant proportion of the original cohort (n=10) between September and November

2020, during a break in the lockdown period. Nonetheless, some participants, for example P9, were not monitored before strict lockdown measures were re-introduced by the UK Government.

It is almost inevitable that the original design of the study involving monitoring participants in both hospital and the community separated by equal time increments was not practically possible. Indeed, at all times, the researcher had to comply with the demands and wishes of each of the participants and the needs of their respective carers. During the study, it became increasingly evident that both the functional rehabilitation phase and the transition to community represented a turbulent and unpredictable period in the rehabilitation journey of a PWSCI. Therefore, it was necessary to monitor participants at times considered appropriate for both the participant and their clinical team. This was particularly relevant for the monitoring period in the community. Accordingly, considerations were made to accommodate medical procedures, therapy, illness, travel or COVID19 shielding/self-isolating. It should be acknowledged that it would have been ideal to follow up each participant at equal increments.

It is also notable all patients were given one IPUPP at timepoint 1, however only the four participants followed for timepoint 2 received two IPUPPS This inevitably would make an impact in the follow up and analysis of participants in the community. It would have been preferable for all participants to have been followed up at timepoint 2 and subsequently received the same number of IPUPPs.

Adapting the XSENSOR SS to perform long term monitoring whilst the participant was mobile in the wheelchair presented some substantial challenges. The CPM system recorded the pressure data via a tablet computer, which required a substantial amount of battery power. This was resolved partly by the manufacturer providing an external battery and adapted backpack. However, this addition proved an inconvenience for those participants in active wheelchairs, which are particularly difficult to balance and lower to the floor. A second issue involved the data logging system. The existing tablet would not store the data unless it had disconnected from the wireless connector and mat, whilst the power remained active, or saved manually before shutdown. When the tablet was shut down before either of these intervening steps, there was a complete loss of data. Therefore any failure, such as if the external battery become disconnected, resulted in an inability to save the data and the necessity to repeat the monitoring period.

The mat was not connected to the wheelchair cushion, but merely placed on top of the support surface. This was problematic for participants who were more active in their wheelchairs, for example P12, as the mat would slide and crease during movements. This resulted in participants removing the pressure mat themselves on two occasions during the monitoring period. Both the bed mat and the wheelchair mat were subject to creasing after activity, which would create false elevations in peak pressures that needed to be accommodated in the subsequent data analysis. One such example is illustrated in Figure 8.1. This pressure distribution was acquired from P8 on a particularly active night in terms of movement, which resulted in creases in the mattress CPM mat. These creases could also create a pressure gradient against the skin, which the researcher monitored carefully.

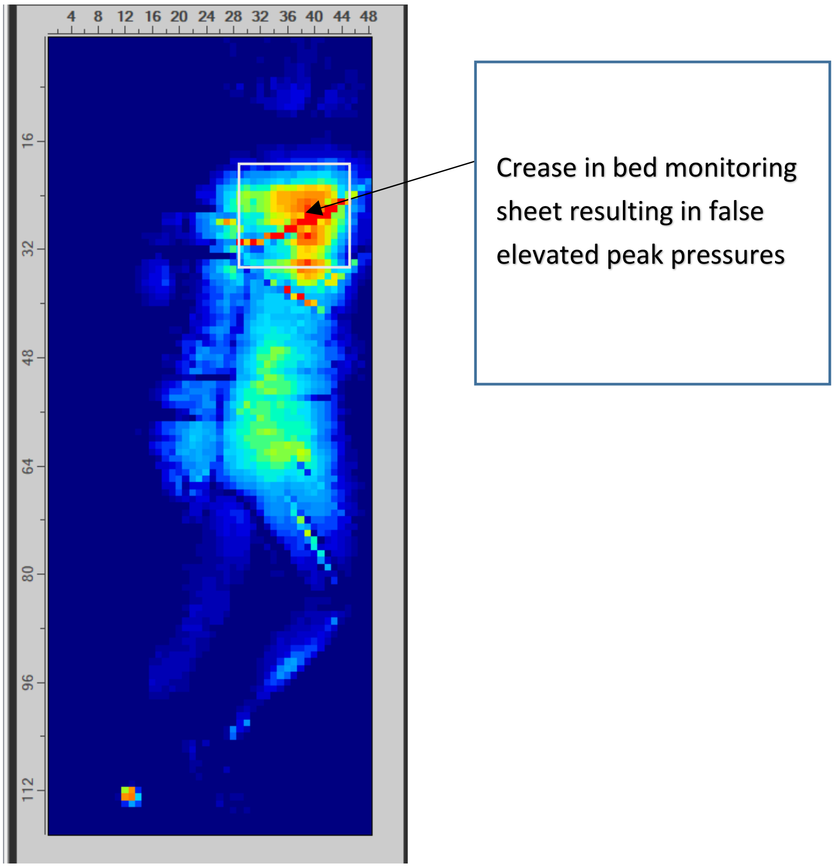


Figure 8.1 Image demonstrating elevated peak pressures due to creases in mattress CPM mat.

The narrative literature review provided key themes of pressure ulcer prevention in PWSCI, including the use of technologies. To date, there is a relative paucity of studies evaluating the feasibility and effectiveness of physical sensors to promote pressure ulcer prevention strategies, thus precluding any meta-analysis of study data. A systematic review may have provided the scope to identify different studies in the literature. However, the methodology employed in the review (Chapter 2) enabled the extraction of meaningful information from both scientific and grey literature during the evidence synthesis and critical appraisal.

It is also relevant that this study involves a small number of participants; subsequently the results and conclusions are tentative. This will be further addressed in section 8.4.

8.3 Novel aspects of the research including advancement in scientific understanding

Participants recruited to this study represented a wide range of features in terms of spinal level and severity of injury (Table 5.1). The present study found a general increase in the frequency of movement in those with a lower level of spinal injury, in lying position, in the inpatient setting (Figures 5.31, 5.32, 5.37 and 5.38). This was the case for movements both lying on a mattress and sitting on a wheelchair cushion. An increase in maximum intervals between movements was detected in those with severe injuries, i.e. ASIA A. These differences in movement patterns were observed despite the specialist care each patient received from the multidisciplinary team (MDT). Indeed, the level of injury and ASIA score appear to be key considerations in providing personalised interventions to support mobility.

These findings represent for the first time that the movement profiles could be analysed in relation to intrinsic factors associated with each PWSCI. This observation supports previous pressure ulcer prevalence studies, which reported a relationship between level of SCI and PUs (Brienza et al. 2017). However, the other studies to date have predominantly focused on seating mobility. In addition, although other studies have examined the frequency of movement after SCI, whereas the role of the level and severity of injury per se have not been previously investigated. Thus while, for example, Hubli et al. (2021) demonstrated that a feedback system based on textile technology could improve compliance to pressure relieving activities in sitting, h there was no subsequent discussion of movement characteristics in relation to the SCI level. Indeed, the present findings related to movement behaviour of PWSCIs in lying and sitting represent a major advance in the scientific understanding of individual risk of developing PUs and could inform personalised prevention strategies based on intrinsic factors.

This study collected data on multiple aspects of skin management after SCI, including history of skin health. It is noteworthy result that patients with both high and low levels of injury/severity after SCI were shown to be skin damage (Section 5.5). Participants with high level of injury who moved infrequently, such as P9 and P13, presented with experiences of bed rest due to skin damage. By contrast, P5, who had a low level of injury and moved frequently on the mattress, also had previous experience of bedrest to skin damage. A similar result was found in a recent study, which had investigated the correlation between function and skin damage in older adults. This study suggested both too little and excessive movements could lead to vulnerability of pressure-induced damage (Moda Vitoriano Budri et al. 2020). Mobility has been considered a key component of pressure ulcer prevention (Sprigle et al. 2020). However, there is a dearth of literature using objective monitoring of at risk individuals and very little data monitoring those during periods of acquired skin damage. With the expanding sophistication and availability of sensing technologies and associated computational analysis, new opportunities to assist limited mobility in self-managed care are emerging. In particular, integrating monitoring, support, and feedback technologies are recommended to promote situational awareness, adherence, and access to professional resources from MDTs. Indeed, it has been long been suggested that education and self-management strategies for those with chronic illness are integral to high quality care (Bodenheimer et al. 2002)

The thesis contains descriptions of monitoring of participants in both inpatient (Chapters 5 and 6) and community settings (Chapter 7). As discussed in Chapter 1, PWSCI are discharged to a wide range of settings in the community after functional rehabilitation, including nursing homes, a further neuro rehabilitation centre, or their private residence. This circumstance was recently described and investigated for PWSCI in Montreal, with three main factors cited as reasons of failure to return private residence after rehabilitation. These were living alone, high cervical injury or an increased length of stay. This aspect of the current study revealed that when participants are placed in different environments, with a range of carer capacities, support surfaces and repositioning techniques, the trends between movement-related parameters were shown to be less evident. As an example, while the trend between the frequency of MOVAs per hour and level of injury in the sitting position was notable in the inpatient setting (Figure 5.37) this was not the case in the community setting (Figure 7.18). With the present findings, it appears that the diminished trends in the relationships between frequencies of movements evident in the community setting, strongly suggest that the vagaries of the environment influence the movement profiles of the SCI individuals. This represents a further novel aspect of this work. Indeed, the current study is the first to successfully investigate the transition between functional rehabilitation and the community setting in terms of movement behaviour.

As previously mentioned, this study utilised CPM with PWSCI on two occasions in the hospital setting (Chapter 5 and 6), and one in the community (Chapter 7). This enabled the monitoring of two participants, P1 and P4, in both lying and sitting positions at each of the three timepoints. The lying results for P1 at timepoint 3 were affected by the introduction of lateral turning system, which has been addressed in Chapter 7 and in section 8.1 of the discussion. However, seating results from these participants from all three time-points are of particular interest and warrant further discussion. Figure 8.2 demonstrates that both participants demonstrated a degree of improvement in terms of movement behaviour, but at different time-points. P1 showed vast improvement in terms of frequency of movement whilst in the hospital setting. Indeed no MOVAs were detected at timepoint 1, whereas an increase to 0.78 average number of MOVAs per hour were detected at timepoint 2. This value decreased to 0.33 MOVAs per hour at timepoint 3, although this value represented a substantial improvement from the first dataset. In contrast, there was a sharp decline in average number of MOVAs for P4 between timepoint 1 and 2, but an improvement at timepoint 3 (Figure 8.2). These findings reveal clear differences between the movement behaviour of the two participants over the three monitoring periods. This demonstrates the need for personalized planning and care. PWSCI have varied motivations, improvements and challenges at different points in their rehabilitation. It can be suggested that intervention at multiple timepoints is essential in education and habit forming for skin health. Care planning and recommendations need to be adaptable to the circumstance a PWSCI finds themselves at a particular time. Environment, physical and mental health circumstances can change frequently during the first two years after SCI. Clinical advice informing PU prevention should encompass all these factors. CPM integrated with a behaviour change intervention, can provide a holistic strategy to achieve the optimum management goals, as have been partly demonstrated in the current study.

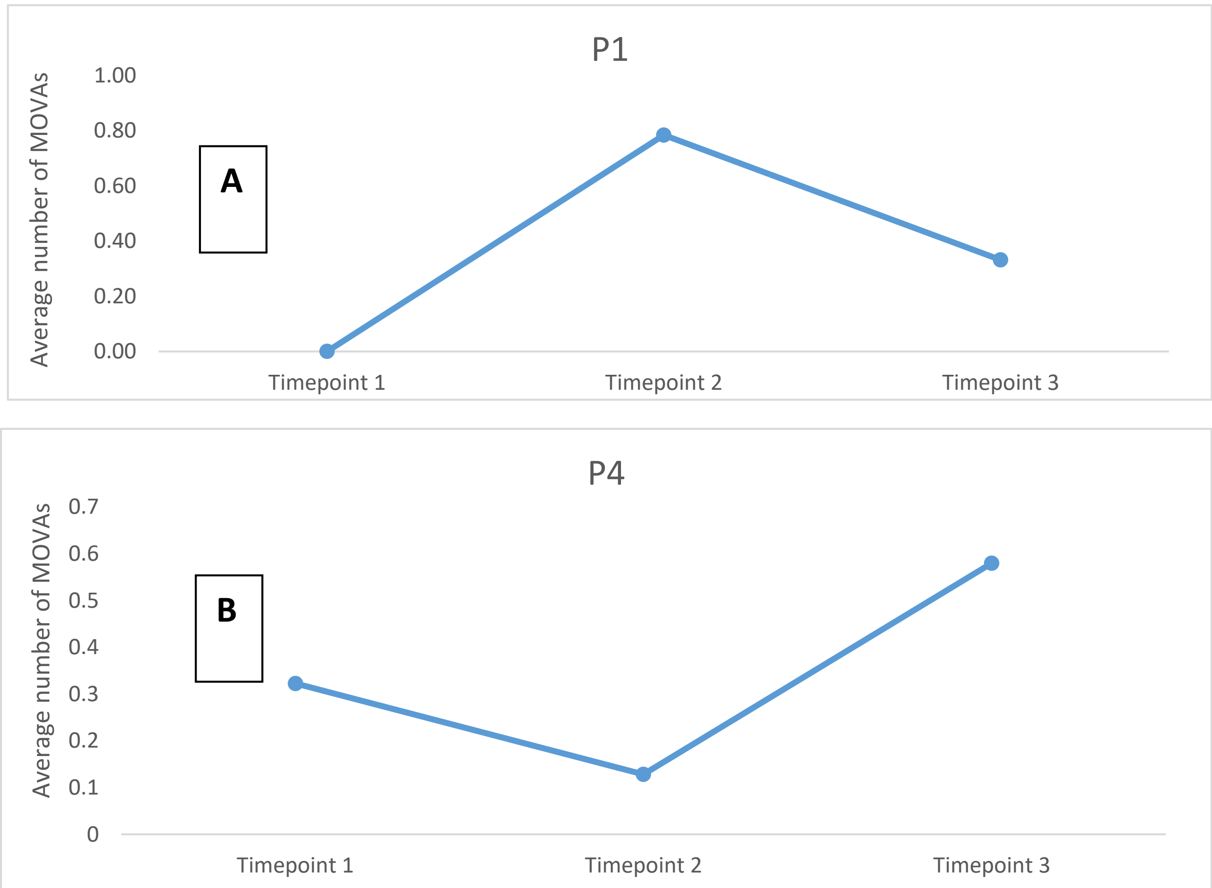


Figure 8.2: Average number of MOVAs, timepoint 1 2 3 (A) P1 (B) P4

A notable result from the current work was the discovery that patients with severe injuries, for example those with cervical injuries and an ASIA score of A or B, are more likely to be in a static position for periods in excess of 6 hours at a time. This situation was made worse in the community with the overreliance on specialised support surfaces and tilting systems, with two participants who had low levels of function, namely P11 and P13 (Tables 7.6, 7.8). P11 was placed on an APAM, and both peak pressures and time between MOVAs increased (Figures 7.12, 7.13) By contrast, P13 was prescribed an automatic lateral turning system when discharged to the community, which replaced the practice of manual turning in the hospital during the night. As previously described, the repositioning provided by the lateral turning system was limited when compared to that provided by the manual turning protocol (Figure 7.7).

Researchers in the host lab have recently developed an algorithm, based on a training set using healthy participants adopting prescribed postures, which was translated to predict movement in the lying position for PWSCI from the present data set (Caggiari et al. 2021). In Chapter 5, the results predicted by the algorithm were compared to the results derived from clinical observations, which have been detailed in Chapter 4. Findings indicated a statistically significant correlation between the performance of the two methods, when considering the selected movement parameters. However, for each individual, the number of movements per hour predicted by the algorithm was consistently higher than those derived from clinical observation (Figure 5.39). These differences could be attributed to the fact that the algorithm was designed to be sensitive to the detection of smaller scale movements (Caggiari et al. 2019). When examining aspects of PU prevention it is essential to investigate small scale movements, as small weight shifts could potentially impact on PU risk, as reported in small study by Sonenblum and Sprigle (2018). Therefore, the adoption of this algorithm represents an important step in automated analysis of CPM data, where the large data sets required substantive time to analyse manually.

It can be suggested that an assessment of movement behaviour and an individualized plan are especially important for those with a chronic injury, such as SCI. Recommendations, such as two to four hourly repositioning strategy throughout the day and night-time, are challenging to maintain and integrate into an active lifestyle. To place this into context, 3 of the participants in this study were under the age of 30. There is potential for those individuals to be living with this injury in excess of 50 years. For this group PU prevention needs to be feasible, acceptable and self-managed where possible. The advancements outlined in the current study represent a crucial step towards this. It would be advantageous to integrate a reliable assessment of movement behaviour and individualized planning into PU prevention guidelines. This would allow for those with chronic conditions which effects mobility, such as SCI, to be comprehensively considered in the recommendations.

The current study also has relevance in other health conditions. Underlying disease in older adults often presents as decline in mobility. This is recognized by geriatricians and has resulted in an effort to quantify older adult mobility through effective clinical tools. Indeed, both clinicians and patients would benefit from integrated, automated mobility analyses for consistent and unobtrusive assessment and tracking of mobility and consequent health. This research has the potential to inform clinicians far beyond that of pressure ulcer risk, as part of a digital platform to monitor health and mobility. Indeed, The NHS Long Term Plan stipulates that developments in health technology and personalized medicine are key for efficient, safe and person centred care (NHS 2019). The current study represents feasible strategies for integrating both of the aforementioned components into the clinical care of multiple patient groups.

In summary, this study has produced novel findings in the following key areas:

- The successful use and analysis of CPM data as a measure of movement behaviour in long term monitoring of PWSCI in both hospital and community settings
- The observation of a general increase in the frequency of movement according to lower level of injury, on both mattress and wheelchair cushion
- The detection of an increase in maximum interval between movements according to severity of injury i.e. ASIA A, both on mattress.
- PWSCIs were observed to have episodes of skin damage with both low levels of movement in lying and sitting positions, as well as extreme high levels of movement.
- A change in PWSCI movement behaviour was evident, when the individual was transferred from the functional rehabilitation phase as an in-patient to the community setting
- The vulnerability of PWSCI with severe cervical injuries, in terms of adopting a static posture for periods in excess of 6 hours, and an over reliance of prescribed medical devices for PU prevention, in the form of pressure off-loading, in community settings.
- An IPUPP in combination with biofeedback can improve frequency of movement, particularly in those who have previous experience of bed rest due to PUs. However, to engage with all PWSCI, healthcare professionals must provide more motivation and education into the risks of developing skin damage, in the form of pressure ulcers, in order to establish an effective personalised IPUPP.

By collaborating with other researchers in the host lab, this study has also advanced scientific understanding in the following areas:

- Clarifying data processed with a computational algorithm to detect equivalent macro-movement patterns in PWSCI as produced by clinical observations, but also provides additional detection of small-scale movements, which may be critical in alerting risk to vulnerable skin areas.

Figure 8.3 represents a schematic, which encompasses all the key stages of the current intervention described in this study, key information which instructed the interventions, and future work as discussed in the subsequent section.

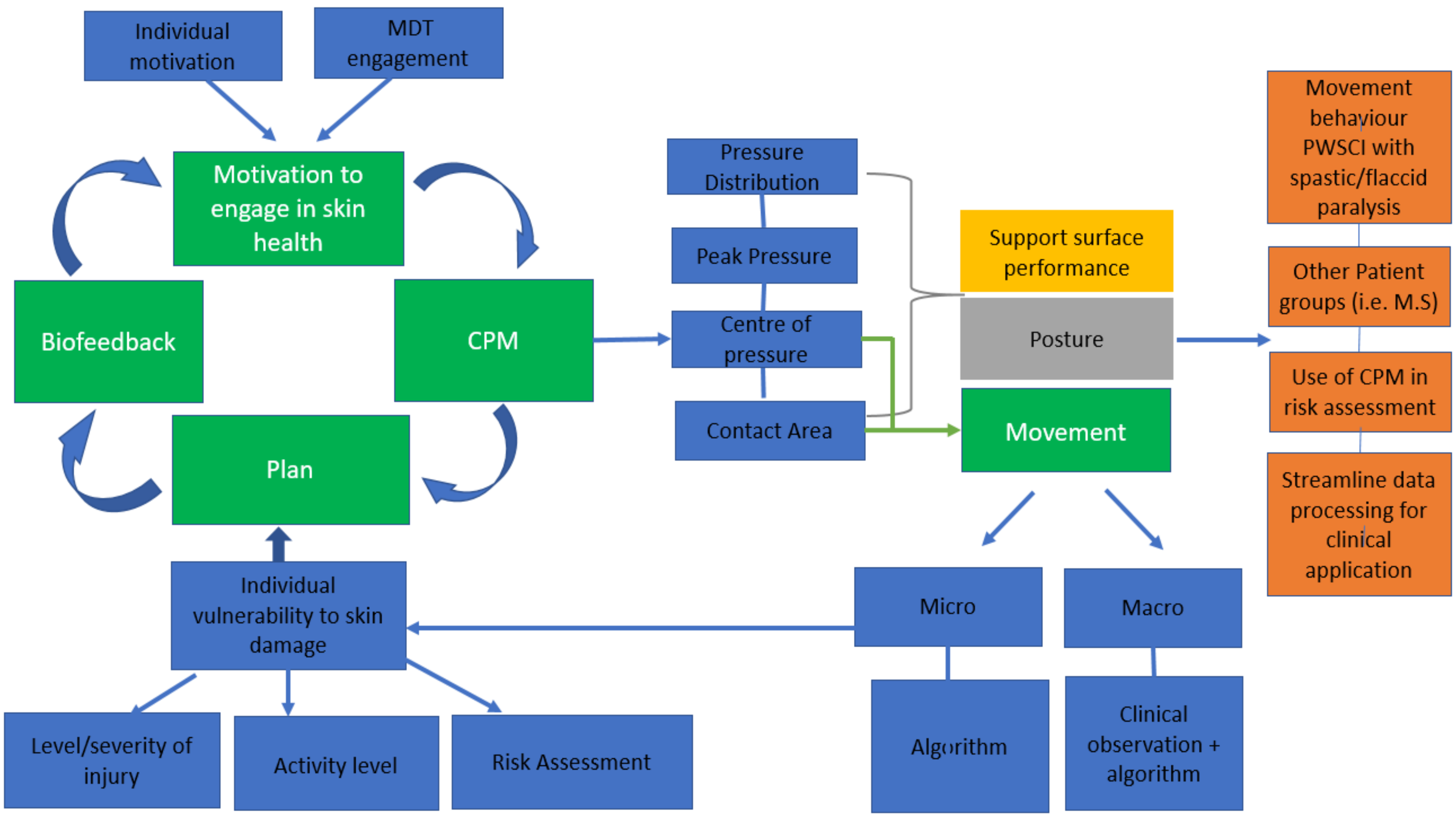


Figure 8.3 Schematic representing key intervention stages, information which instructed each stage of the intervention and future work.

Represents key stages of the intervention

Represents information which instructs the key stages of the intervention

Represents future work

8.4 Future work

It is perhaps unexpected that the movement behaviour, in the form of two selected parameters, of such a heterogeneous small cohort of PWSCI participants should produce significant trends between both their diverse range of spinal levels of injury and ASIA scores. This provides encouragement to extend this work to include a larger cohort of PWSCIs. This would permit cluster analysis of individuals with similar spinal levels and/or functional scores to examine the influence of other intrinsic features in affecting movement behaviour and/or risk of PU development. The study design could be extended to other specialist SCI centres to examine the effects of local clinical practices and routines in terms of prevention strategies and care to management of vulnerable PWSCI patients. It would be important that, where possible, the different centres would adopt standardised test protocols.

As discussed in Chapter 5, current pressure monitoring systems produce large datasets. Reducing these data sets to a form they can be utilized for the identification of movement behaviour is inevitably time consuming. Accordingly, in order to use this technology to identify movement efficiently within the constraints of clinical practice, this process needs to be automated and streamlined. Indeed, it is critical that redundant data is identified and removed, so that the focus is on the critical pressure-related parameters. A first approach to achieve this goal was demonstrated in Chapter 5 with the use of an algorithm, developed as part of a separate PhD project (Caggiari et al. 2020), to detect movement profiles from both lying and sitting data sets. Dependent on the thresholds imposed on the pressure signals, both micro- and macro-movements could be detected in the form of postural changes and postural adjustments, respectively (Caggiari et al. 2021). The algorithm needs further refinement so that it is based on training data derived from patient groups adopting relevant postures in lying and sitting. It also needs to be evaluated by various members of a multidisciplinary team, including nurses, therapists and clinical technicians, to test its effective use in the clinic.

The detection of micro-movements could be particularly pertinent when monitoring PWSCIs in both the hospital and community settings. Indeed in a study involving 29 participants with varying levels of SCI, it was reported that frequent episodes of micro-movements, as estimated from an in-built weight shift monitor composed of force sensors, resulted in a reduced incidence of PUs

(Sonenblum and Sprigle 2018). It would be of benefit to further examine this correlation using the existing pressure monitoring technologies and developing the computational methods introduced in the current study.

It would also be beneficial to extrapolate the key findings of this study to other vulnerable patient groups. As an example, a study could be introduced to involve the use of CPM in a cohort of patients with Multiple sclerosis (McGinnis et al. 2021). This condition involves a neurological motor deficit with intact cognitive function, which allows for maximum engagement and benefit from this technology. Although it is accepted that SCI and MS present with different health trajectories, with the former being chronic in nature and the latter degenerative. This difference may have an impact on both the motivation and engagement of the technology. Indeed in a study examining the engagement with telehealth for wound management, it was reported that those individuals with MS engaged almost twice as often as those with SCI (Mercier et al. 2015).

An extension of the work could involve examination of the relationship between the different forms of muscle paralysis i.e. flaccid or spastic, and the movement behaviour during prolonged support. In particular, it would be appropriate to assess whether the degree of paralysis affects the nature of the movements in terms of both macro- and micro-movements. Indeed, a previous study examined tissue oxygen levels at the ischial tuberosities in both paraplegia and quadriplegia patients in their rehabilitation phase and then at 2-4 weekly intervals (Bogie et al. 2005). The authors reported that tissue oxygen levels deteriorated with time for those with paraplegia whereas they improved for those with quadriplegia. This suggests that with flaccid paralysis the loss of muscle bulk with an associated increase in fat infiltration in load- bearing tissues results in an increased risk of tissue damage.

In the future CPM could be used in PU risk assessment and intervention strategies. As previously discussed, it may be beneficial to conduct a full systematic review of the current literature. Much of the literature surrounding PU prevention strategies involves the efficacy of different support surface technologies. However, in depth examination of movement behaviour is not currently employed in risk assessment. This is evident in both literature and clinical practice, as demonstrated by current best practice guidelines. It is well accepted, however, that in order to integrate movement behaviour into PU risk guidelines, safe threshold levels need to be established for skin health, ideally on a personalised level. This would require further work examining the characteristics of movement behaviour in patients presenting with a spectrum of status from healthy intact skin, to early signs of skin damage to areas presenting with various grades of pressure ulcers, including deep tissue injury (DTI).

Appendix 1 Individualised pressure ulcer prevention plans (IPUPP)

(IPUPP) P1

Affix patient label here

Level of Injury: T6

Time since injury: 9 months

Plan number: 2 15/2/19

Aspect of care	***Current***	***Recommendation***
Wheelchair cushion.	Foam + Fluid tripad with solid insert JAY 2	No further recommendation
Mattress.	Air- based Talley Quatro Plus	No further recommendation
Time in wheelchair.	6 hours	No further recommendation
Pressure relieving technique.	Forward lean onto table (2-3 minutes)	1) Forward lean onto table (2-3 minutes) 2) Forward lean, arms crossed in front (2-3 minutes) 3) Rock side to side for 2-3 minutes (angle on each side not sustained for full 2-3 minutes – to ensure no adverse effect on

		fluid insert in cushion)
Pressure relieving movement intervals	2 hours	1 hour
Turning technique whilst in bed	On back – (pillow underneath each leg) On right- (pillow supporting back in log shape , 2 pillows underneath left leg, one underneath right)	No further recommendations
Turn intervals whilst in bed	4 hours on back 5 hours on left side	3 hours on back 5 hours on right side
Posture	Ensure sat back in chair fully	No further additions.

(IPUPP) P4

Affix patient label here

Level of Injury: T10

Time since injury: 3 months

Plan number: 1

Date: 7/6/19

Aspect of care	***Current***	***Recommendation***
Wheelchair cushion.	Invacare Matrix Flocare Solution Foam, Seat Rigidiser	Will liaise with pressure clinic
Mattress.	Premier Spinal Foam Mattress	NONE
Time in wheelchair.	6-7 hours	NONE
Pressure relieving technique.	No noticeable displacement of pressure during seating sessions	Forward lean, resting on arms, for 2-3 minutes
Pressure relieving movement intervals	N/A	Every hour
Turning technique whilst in bed	Self-turning	NONE
Turn intervals whilst in bed	3-4 hourly	NONE

Posture	Possible pelvic obliquity to left	Will liaise with pressure clinic
Other advice	High pressure created when sitting upright in bed. This occurs for a number of hours in morning	Have advised to significantly reduce time sitting upright in bed, lower the head of the bed when not eating, drinking or dressing.

IPUPP (P10)

Affix patient label here

Level of Injury: T11

Time since injury: 3 months

Plan number: 1

Date: 28/10/19

Aspect of care	***Current***	***Recommendation***
Wheelchair cushion.	Matrx libra foam/fluid cushion	No change
Mattress.	Softform premier pro (castellated foam)	No change
Time in wheelchair.	6-8 hours	No change
Pressure relieving technique.	Small changes in position for 1-2 minutes	***Side leans to offload tissues, 2-3 minutes***
Pressure relieving movement intervals	2 hourly	New technique started 2 hourly
Turning technique whilst in bed	Self-turning	No change
Turn intervals whilst in bed	2-4 hourly	No change
Posture	Appears to be seated predominantly on left and	Have re-iterated information to patient and

	placing pressure on right hip	will contact therapists for posture assessment
Other advice		Be aware sitting-up in bed can create high pressures, reduce this where possible.

Appendix 2 Pressure ulcer prevalence collection Sheet (European Pressure Ulcer Advisory Panel 2002)

SUMMARY REPORT ON THE PREVALENCE OF PRESSURE ULCERS

38077

Hospital identification number 0 1 2 3 4 5 6 7 8 9

European Pressure Ulcer Prevalence Study

Minimum Data Set

epuap

General Data

Setting
- O University Hospital
- O General Hospital
- O Local Hospital

Number of Beds
- O > 1000
- O 500 - 1000
- O < 500

Country
- O Belgium
- O Denmark
- O Finland
- O France
- O Germany
- O Greece
- O Hungary
- O Italy
- O Netherlands
- O Portugal
- O Spain
- O Sweden
- O United Kingdom
- O Other

Patient Data

Age
- O < 12
- O 12 - 18
- O 19 - 39
- O 40 - 59
- O 60 - 69
- O 70 - 79
- O 80 - 89
- O > 89

Gender
- O Female
- O Male

Care Group
- O Neurology / Rehabilitation
- O Intensive
- O Chronic Care
- O Acute Care / High Dependency

Expected Length of Stay
- O < 6 days
- O 6 days - 1 month
- O > 1 month

Braden Scale

Sensory perception	Moisture	Activity
O Completely limited	O Constantly moist	O Bedfast
O Very limited	O Very moist	O Chairfast
O Slightly limited	O Occasionally moist	O Walks occasionally
O No impairment	O Rarely moist	O Walks frequently
Mobility	**Nutrition**	**Friction and Shear**
O Completely immobile	O Very poor	O Problem
O Very limited	O Probably inadequate	O Potential problem
O Slightly limited	O Adequate	O No apparent problem
O No limitations	O Excellent	

Incontinence

Incontinence
O Not
O Occasional
O Usually/Urine
O Double

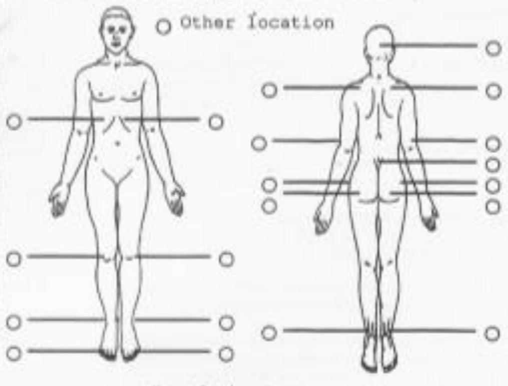
Skin observation

Most severe pressure ulcer
- O None
- O Non-blanchable erythema
- O Blister / Abrasion
- O Superficial ulcer
- O Deep ulcer / Necrosis

Location(s) of most severe pressure ulcer(s)
- O Sacrum
- O Heel
- O Hip
- O Other

All existing pressure ulcers

O Other location



Prevention

Equipment

In bed
- O No special equipment
- O Non-powered device
- O Powered device

In chair
- O No special equipment
- O Non-powered device
- O Powered device

Repositioning

In bed
- O No planned/Irregularly
- O Every 2 hours
- O Every 3 hours
- O Every 4 hours

In chair
- O No planned/Irregularly
- O Every 2 hours
- O Every 3 hours
- O Every 4 hours

Appendix 3 Interview questions for timepoint 1 and 2 adapted from Integrated Behavioural Model (Montano and Kasprzyk 2015)

Timepoint 3

1) What do you like/dislike about your current PU prevention methods?
2) What are some the advantages/disadvantages of your current PU prevention methods?
3) Is there anybody who does support/does not support you in carryong out PU prevention?
4) What things make it easy/hard for you to carry out PU prevention?
5) What other factors affect your ability to carry out PU prevention?

Timepoint 2

1) What do you like/dislike about you PU prevention IPUPP?
2) What are some the advantages/disadvantages of the IPUPP?
3) Is there anybody who would support/not support you carrying out the IPUPP?
4) Who can you think of that would/would not do the IPUPP?
5) What things would make it easy/hard for you to do the IPUPP?
6) If you want to carry out the IPUPP long term, how certain are you that you can?
7) What other factors could affect your ability to carry out the IPUPP?

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