BALANCE CONTROL IN DANCE POSITIONS

by

Eunhye Huh

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ABSTRACT

Balance Control in Dance Positions

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The purpose of this thesis is to develop and understand dance balance characteristics on various kinds of dance, related positions and shoe types which contribute to dance performance and to understand different balance controls in various groups. The first study was conducted to examine balance into ballet 2nd position between Ballet shoes and Pointe shoes. Eight dancers performed five different conditions in ballet 2nd position (Ballet Flat, Ballet Demi, Pointe Flat, Pointe Demi, and Pointe Toe) and Centre of Pressure (COP) was used to assess balance. The second study was testing balance control and response to perturbations whilst standing on double leg stance dance positions using a moving platform. Four dance positions were performed by eight subjects (Normal Flat, Turnout Flat, Normal Demi and Turnout Demi) and the platform was moved in two different directions (Forward and Backward) at two different speeds (slow and fast). Kinetics, Kinematics and EMG data was taken from this study. The third study was taken to compare balance control and response to perturbations in single leg standing dance positions between eight dancers and eight gymnasts. The subjects performed static single leg balance in Normal Flat, Turnout Flat, Normal Demi and Turnout Demi. Also, perturbed stance trials were collected in anterior, posterior, right and left directions for two dance positions (Normal Flat and Turnout Flat) at two different speeds (slow and fast) on the moving platform. The results from the studies indicate that dancers move in Medial - Lateral direction more than in Anterior - Posterior direction on Demi-pointe and Toe standing by performing plantar flexion during ballet 2nd position. Demi-pointe position may cause longer delay of EMG latencies because CNS is probably sending information already to keep correcting balance on Demi-pointe. Dancers and Gymnasts have different balance controls due to their ways of training in their performance. Dancers generally reacted faster with slow perturbation in Turnout stance than Gymnasts because this is the particular condition which Dancers are training in.

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Thanks to my parents for the amazing support. My parents really did their best! I would like to write a message for them in Korean. 모든 지원을 아끼지 않고 최선을 다해주신 부모님 감사합니다. 그 동안 정말 고생 많으셨어요. 항상 건강 조심하세요!

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TABLE OF CONTENTS

ABSTRACT ..... **i**
ACKNOWLEDGEMENTS ..... **ii**
TABLE OF CONTENTS ..... **iv**
LIST OF FIGURES ..... **ix**
LIST OF TABLES ..... **xiii**

CHAPTER 1: INTRODUCTION **1**
1.1. Area of study 1
1.2. Statement of Purpose 5
1.3. Research Questions 5

CHAPTER 2: REVIEW OF LITERATURE **10**
2.1. Balance and Posture Control 10
2.2. Static and Dynamic Posturography 13
2.3. Understanding stability and Body Sway 18
2.3.1. Stability and Body Sway 18
2.3.2. Linear Stability 19
2.3.3. Rotary Stability 19
2.4. Centre of Pressure and Centre of Mass 22
2.4.1. Definition of the COP and COM 22
2.4.2. Centre of Pressure on the Foot 23
2.4.3. Differences Between the COM and COP During Quite Standing 24
2.4.4. Measuring Balance Control in Both Feet - COP_{net} 26
2.4.5. Inverted Pendulum Model 27
2.4.5.1. M/L and A/P Models 28
2.5. Neurological Control During Balance 30
2.5.1. Somatosensory 30
2.5.2. Vision 32
2.5.3. Vestibular System 32
2.6. Researching into Dance 34
2.6.1. The Need of Dance Study 34
2.6.2. Previous Dance Studies Related to Standing Balance 34
2.6.3. Dancing on Pointe 36
2.6.4. Dance Injuries and Its Prevention 38

CHAPTER 3: METHODS **40**
3.1. Subjects 40
3.1.1. The 1st Study (static balance): A balance study into ballet 2nd position between 2 types of shoes (ballet shoes and pointe shoes) 40
3.1.2. The 2nd Study: Balance control and response to perturbations whilst

standing on double leg stance dance positions using a moving platform 40
3.1.3. The 3rd Study: Comparisons of balance control and response to perturbations in one leg standing dance positions between dancers and gymnasts 41
3.2. Data Collection 42
3.2.1. Kinematics Data 43
3.2.2. Kinetics Data 47
3.2.3. EMG Data 49
3.2.4. Platform Movements 52
3.2.5. Anthropometrics 53
3.3. Procedures 54
3.3.1. The 1st Study: A balance study into ballet 2nd position between 2 types of shoe (ballet shoes and pointe shoes) 55
3.3.2. The 2nd Study: Balance control and response to perturbations whilst standing on double leg stance dance positions using a moving platform 56
3.3.3. The 3rd Study: Comparisons of balance control and response to perturbations in single leg standing dance positions between dancers and gymnasts 58
3.4. Data Processing and Analyses 60
3.4.1. Joint Centres 60
3.4.2. Hip Centres 60
3.4.3. Force Plates Centre 62
3.4.4. Centre of Mass and Body Centre of Mass calculations 62
3.4.5. Centre of Pressure (COP) 63
3.4.4.1. Standard Deviation 64
3.4.4.2. Range 65
3.4.4.3. Sway Path 65
3.4.4.4. ApEn 65
3.4.4.5. DFA 67
3.4.5. EMG Latencies 67
3.4.6. 3D Torque 68
3.4.7. Statistics 71
3.4.7.1. The 1st study 71
3.4.7.2. The 2nd Study 72
3.4.7.3. The 3rd Study 72

CHAPTER 4: BALLET 2nd POSITION IN STATIC CONDITIONS 78
4.1. Standard Deviations about the X axis, Medial-Lateral (SD_X)..... 78
4.2. Standard Deviations about the Y axis, Anterior-Posterior (SD_Y)..... 79
4.3. Range about the X axis of the COP, Medial-Lateral ($Range_X$) 81
4.4. Range about the Y axis of the COP, Anterior-Posterior ($Range_Y$) 81
4.5. Sway Path 82

4.6. $ApEn_X$ 83
4.7. $ApEn_Y$ 85
4.8. DFA_X 86
4.9. DFA_Y 87
4.10. Discussions 88

CHAPTER 5: EMG LATENCIES FROM DOUBLE LEG STANCE DANCE POSITIONS 91
5.1. The Fastest EMG Latencies amongst Six Shank EMG Sensors 91
5.2. Discussions 93

CHAPTER 6: EMG LATENCIES FORM SINGLE LEG BALANCE IN DYNAMIC CONDITIONS 96
6.1. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on both Dancer and Gymnast Groups 96
6.1.1. Dancer Group vs Gymnast Group 97
6.1.2. Foot Positions 98
6.1.3. Directions of Platform Movement 99
6.1.4. Speeds 100
6.2. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on Dancer Group 102
6.2.1. Dancer Group: Foot Positions 102
6.2.2. Dancer Group: Directions of Platform Movement 103
6.2.3. Dancer Group: Speeds of Platform Movement 105
6.3. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on Gymnast Group 106
6.3.1. Gymnast Group: Foot Positions 106
6.3.2. Gymnast Group: Directions of Platform Movement 107
6.3.3. Gymnast Group: Speeds of Platform Movement 109
6.4. Comparisons of the Fastest EMG Latencies amongst 3 Shank EMG sensors between Dancer and Gymnast Groups (Independent samples T test) 111
6.5. The Fastest EMG Latencies amongst 3 Shank EMG Sensors Comparing ‘Foot positions × Directions’ within the Same Speeds in the Separated Groups (One-way Repeated Measures ANOVA) 114
6.5.1. Dancer Group at Slow Speed: Foot positions × Directions 114
6.5.2. Dancer Group at Fast Speed: Foot positions × Directions 116
6.5.3. Gymnast Group at Slow Speed: Foot positions × Directions 117
6.5.4. Gymnast Group at Fast Speed: Foot positions × Directions 118
6.6. Discussions 120

CHAPTER 7: NON-PARAMETRIC AND FREQUENCY ORDER TESTS ON EMG LATENCIES FROM 3 SAHNK MUSCLES ON SINGLE LEG BALANCE IN DYNAMIC CONDITIONS 123

7.1. All Groups between Foot Positions 123
7.1.1. All Groups in Normal Foot Position 123
7.1.2. All Groups in Turnout Position 125
7.1.3. All Groups Comparing Normal and Turnout Positions 126
7.2. Dancer Group between Foot Positions 128
7.2.1. Dancer Group in Normal Foot Position 128
7.2.2. Dancer Group in Turnout Foot Position 129
7.3. Gymnast Group between Foot Positions 132
7.3.1. Gymnast Group in Normal Foot Position 132
7.3.2. Gymnast Group in Turnout Foot Position 133
7.4. Dancers VS Gymnasts in Normal Foot Position 135
7.5. Dancers VS Gymnasts in Turnout Foot Position 137
7.6. Discussions 140

CHAPTER 8: JOINT TORQUE RESPONSES FROM SINGLE LEG BALANCE IN DTYNAMIC CONDITIONS 141
8.1. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis from both Dancer and Gymnast Groups 141
8.1.1. Dancer Group vs Gymnast Group 142
8.1.2. Foot Positions 143
8.1.3. Directions of Platform movement 144
8.1.4. Speeds of Platform Movement 146
8.2. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis based on the separated Dancer and Gymnast Groups 148
8.2.1. Foot Positions 148
8.2.2. Directions of Platform Movement 149
8.2.3. Speeds of Platform Movement 151
8.3. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis in Normal Foot position based on separated Dancer and Gymnast Groups 153
8.3.1. Normal Foot: Directions of Platform Movement 153
8.3.2. Normal Foot: Speeds of Platform Movement 155
8.4. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis in Turnout Foot position based on separated Dancer and Gymnast Groups 157
8.4.1. Turnout Foot: Directions of Platform Movement 157
8.4.2. Turnout Foot: Speeds of Platform Movement 159
8.5. Comparisons of the Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis between Dancer and Gymnast Groups (Independent

samples T-test) ····· 161
8.6. Comparisons of torques in each condition between Dancer and Gymnast Groups (One-way ANOVA) ····· 162
8.6.1. Dancer Group vs Gymnast Group: Normal Foot × Backward ····· 162
8.6.2. Dancer Group vs Gymnast Group: Normal Foot × Lateral ····· 163
8.6.3. Dancer Group vs Gymnast Group: Normal Foot × Medial ····· 164
8.6.4. Dancer Group vs Gymnast Group: Turnout Foot × Forward ····· 165
8.6.5. Dancer Group vs Gymnast Group: Turnout Foot × Backward ····· 165
8.6.6. Dancer Group vs Gymnast Group: Turnout Foot × Lateral ····· 166
8.6.7. Dancer Group vs Gymnast Group: Turnout Foot × Medial ····· 168
8.7. Discussions ····· 169

CHAPTER 9: SINGLE LEG BALANCE CONTROL IN STATIC CONDITIONS 175
9.1. Standard Deviation about the X axis, Medial-Lateral (SD_X) ····· 175
9.2. Standard Deviation about the Y axis, Anterior-Posterior (SD_Y) ····· 177
9.3. Range about the X axis of the COP, Medial-Lateral ($Range_X$) ····· 178
9.4. Range about the Y axis of the COP, Anterior-Posterior ($Range_Y$) ····· 180
9.5. Sway Path ····· 181
9.6. ApEn ····· 183
9.7. DFA ····· 186
9.8. Discussions ····· 189
9.8.1. Dancer groups vs Gymnast group (Q6) ····· 189
9.8.2. Normal foot position vs Turnout foot position (Q4) ····· 190
9.8.3. Single vs Double (Q4) ····· 192

CHAPTER 10: DISCUSSION AND CONCLUSION ····· 194

REFERENCES ····· 206
APPENDIX 1: Informed consent Forms ····· 216
APPENDIX 2: Subject Information Sheets ····· 219
APPENDIX 3: Matlab Codes ····· 228

LIST OF FIGURES

Figure 2.1: The gymnast is standing on the beam. Supporting base (BOS) is the contact area between the foot and the beam and the line of gravity falls within it 19

Figure 2.2: The ballerina is performing arabesque and standing on foot (Dance net, 2008) 19

Figure 2.3: Arabesque balance on tip toes with pointe shoes (Klein, 2011) 20

Figure 2.4: The foot print with COP path. Directions of force vectors are shown in the transverse plane by line segments and path of COP is the closest line to medial side of foot (Cavanagh, 1978) 23

Figure 2.5: A participant sways the body back and forth while standing quietly on a force plate (adapted from Winter, 1995; Winter, 2009) 24

Figure 2.6: Standing inverted pendulum biomechanical models. The frontal plane pendulum model is a parallelogram pivoting about both ankle and both hip joints Winter, 1995) 29

Figure 2.7: A. Pointe shoes balance on tip toes and anatomy of pointe shoe, B. Demi-pointe balance without wearing pointe shoe (Shah, 2009) 37

Figure 3.1: The CAREN system including all other equipment for the studies 42

Figure 3.2: Vicon T series camera (will use my photo in the future) 43

Figure 3.3: Vicon dynamic calibration frame 44

Figure 3.4: Reflective markers used for studies (14 mm & 25 mm) 44

Figure 3.6: Coordinates of true origin, Force, COP and free vertical torque 47

Figure 3.7: Yeadon (1990)'s inertia model which has 40 solid segments in a body 53

Figure 3.8: Five conditions of ballet 2nd position with ballet and pointe shoes 56

Figure 3.9: Ballet 2nd position (standing on both feet & turnout) and Contemporary dance position (standing on both feet & parallel feet, standing with normal feet position) in Flat and Demi-pointe feet conditions 58

Figure 3.11: Markers on hip (right & left ASIS and PSIS) and six created markers including right & left hip joint centres (RHJC & LHJC). The right picture is showing makers on the hip on Vicon 1.7.1. 61

Figure 3.12: Created FPC (Force Plates Centre) gained via using four markers at the edges of the force plates. The right picture is showing markers on the force plates on Vicon 1.7.1. 62

Figure 3.13: An example how to calculate EMG latency and Torque response time from the point where force rises (time = 0) to the EMG burst and Torque rise in ms 68

Figure 3.14: Comparisons of five ballet 2nd positions between types of shoes 71

Figure 3.15: Six Comparisons amongst four dance balance conditions in the 2nd study 72

Figure 5.1: Mean graphs of EMG Latencies (ms) from each foot position (NF: Normal Flat, ND: Normal Demi, TF: Turnout Flat, TD: Turnout Demi) 93

Figure 6.1: Mean graphs of All and Shank EMG Latencies (ms) with comparing Dancer and Gymnast groups 97
Figure 6.2: Mean graphs of the fastest All and Shank EMG latencies (ms) comparing with Normal foot and Turnout foot positions 98
Figure 6.3: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on four directions of platform movement 100
Figure 6.4: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on two speeds and Total (combined) 101
Figure 6.5: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Normal and Turnout foot positions from Dancer group 103
Figure 6.6: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Directions of platform movement from Dancer group 104
Figure 6.7: Mean graphs of the fastest All and Shank EMG latencies depending on Speeds from Dancer group 105
Figure 6.8: Mean graphs of the fastest All and Shank EMG latencies depending on Foot positions from Gymnast group 107
Figure 6.9: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Directions of platform movement 108
Figure 6.10: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Speeds 110
Figure 6.11: Mean graphs of the fastest Shank EMG latencies (ms) at Slow speed with plotting Groups and Foot positions together depending on Directions 112
Figure 6.12: Mean graphs of the fastest Shank EMG latencies (ms) at Fast speed with plotting Groups and Foot positions depending on Directions 113
Figure 6.13: Mean graphs of the fastest Shank EMG latencies (ms) from Dancer group at Slow speed 115
Figure 6.14: Mean graphs of the fastest Shank EMG latencies (ms) from Dancer group at Fast speed 117
Figure 6.15: Mean graphs of the fastest Shank EMG latencies (ms) from Gymnast group at Slow speed 118
Figure 6.16: Mean graphs of the fastest Shank EMG latencies (ms) from Gymnast group at Fast speed 119
Figure 8.1: Mean graphs of All and Main Torque Responses (ms) and comparison between Dancer and Gymnast groups 142
Figure 8.2: Mean graphs of All and Main Torque Responses (ms) and comparison between Normal and Turnout foot positions 143
Figure 8.3: Mean graphs of All and Main Torque Responses (ms) depending on four direction of platform movement 144
Figure 8.4: Mean graphs of All and Main Torque Responses (ms) depending on speeds of platform movement 147
Figure 8.5: Mean graphs of All and Main Torque Responses (ms) and comparison between Normal and Turnout foot positions in separated groups (Dancers and

Gymnasts) 149
Figure 8.6: Mean graphs of All and Main Torque Responses (ms) and comparison between four directions in separated groups 151
Figure 8.7: Mean graphs of All and Main Torque Responses (ms) and comparison between the speeds of platform movement in separated groups 152
Figure 8.8: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups 154
Figure 8.9: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups 156
Figure 8.10: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups 158
Figure 8.11: Mean graphs of All and Main Torque Responses (ms) in Turnout foot position and comparison between the speeds of platform movement in separated groups 160
Figure 8.12: Mean graphs of All and Main Torque Responses (ms) in Turnout foot position + Forward Direction + Slow platform movement and comparison between the separated groups 161
Figure 9.1: Comparisons of SD_X means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] 177
Figure 9.2: Comparisons of SD_Y means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] 178
Figure 9.3: Comparisons of $Range_X$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05**)** 179
Figure 9.4: Comparisons of $Range_Y$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 181
Figure 9.5: Comparisons of Sway Path means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 182
Figure 9.6: Comparisons of $ApEn_X$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 185
Figure 9.7: Comparisons of $ApEn_Y$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 186
Figure 9.8: Comparisons of DFA_X means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 188

Figure 9.9: Comparisons of DFA_Y means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05) 188
Figure 10.1: A diagram of results from the 1st study (Ballet 2nd position in static conditions) depending on multiple balance metrics 195

LIST OF TABLES

Table 2.1: Recording equipment and outcome measures depending on types of modality in posturography (Bloem et al, 2003) 13

Table 2.2: External and Self-inflicted perturbations in dynamic posturography (Bloem et al., 2003) 16

Table 3.1: Means and Standard Deviations (SD) of subjects information in groups depending on genders 41

Table 3.2: Marker placement and created segments to collect kinematic data 45

Table 3.3: Attachments of EMG sensors for the 2nd study 50

Table 3.4: Attachments of EMG sensors for the 3rd study 51

Table 3.5: The changes of body segments in three different versions - 11 original segments, Yeadon (1990)'s 40 solid segments and re-calculated segments (reduced numbers of segments) for the 2nd and 3rd studies 54

Table 3.6: Numbers of trials depending on dance positions and shoes performed by each subject 55

Table 3.7: The description of dance positions and external perturbations regarding trials performed by the subjects 57

Table 3.8: The description of balance test sessions, positions and external perturbations regarding trials performed by each subject (N: Normal, T: Turnout, S: Slow 5 cm at 5 $cm.s^{-1}$, F: Fast 10 cm amplitude at 10 $cm.s^{-1}$) 59

Table 3.9: Designs of statistical tests used on mean values of EMG latencies 73

Table 3.10: An example of counting Frequency orders in Turnout Backward at Slow from a group (the 1st reaction muscle: in Red, the 2nd reaction muscles: in Orange & the 3rd reaction muscle: in Yellow at the bottom part of this table) 74

Table 3.11: An example of calculating $\%_A$ and $\%_B$ based on Total Numbers of each muscle from Table 3.10 ($\%_A$: in Blue, $\%_B$: in Green) 76

Table 3.12: An example of calculating $\%_A$ and $\%_B$ based on Total Numbers of each muscle from Table 3.10 ($\%_A$: in Blue, $\%_B$: in Green) 77

Table 4.1: Means and SD of Standard Deviations on X (ML) axis (SD_X) from COP_{net} with different types of shoesand feet positions (Sig. < 0.05) 79

Table 4.2: Means and SD of Standard Deviations on Y (AP) axis (SD_Y) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05) 80

Table 4.3: Means and SD of Range on X (ML) axis ($Range_X$) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05) 81

Table 4.4: Means and SD of Range on Y (AP) axis ($Range_Y$) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05) 82

Table 4.5: Means and SD of Range from Sway Path with different types of shoes and feet positions (Sig. < 0.05) 83

Table 4.6: Means and SD of Range from $ApEn_X$ with different types of shoes and feet positions (Sig. < 0.05) 84

Table 4.7: Means and SD of Range from $ApEn_Y$ with different types of shoes and feet positions (Sig. < 0.05) 85
Table 4.8: Means and SD of Range from DFA_X Long Range with different types of shoes and feet positions (Sig. < 0.05) 86
Table 4.9: Means and SD of Range from DFA_Y Long Range with different types of shoes and feet positions (Sig. < 0.05) 87
Table 5.1: Means and SD of EMG latencies (in ms) with different feet positions (Sig. < 0.05) 92
Table 6.1: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Dancer and Gymnast groups 97
Table 6.2: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions 98
Table 6.3: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors in four directions of platform movement 99
Table 6.4: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst Slow, Fast and combined Total speeds of platform from all EMG sensors 100
Table 6.5: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions based on Dancer group only 102
Table 6.6: Mean and SE (Standard Error) values of EMG latencies amongst (in ms) all EMG sensors and three Shank EMG sensors in four directions of platform movement based on Dancer group only 103
Table 6.7: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors at Slow, Fast and combined Total speeds of platform based on Dancer group only 105
Table 6.8: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions based on Gymnast group only 107
Table 6.9: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors in four directions of platform movement based on Gymnast group only 108
Table 6.10: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors at Slow, Fast and combined Total speeds of platform based on Gymnast group only 109
Table 6.11: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors with two foot positions in four directions at Slow, Fast speeds of platform movement (Independent samples T test was ran) 111
Table 6.12: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Dancer group with two foot positions in four directions at Slow speeds of platform movement 114

Table 6.13: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Dancer group with two foot positions in four directions at Fast speeds of platform movement 116

Table 6.14: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Gymnast group with two foot positions in four directions at Slow speeds of platform movement (One-way Repeated measures ANOVA was ran) 118

Table 6.15: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Gymnast group with two foot positions in four directions at Fast speeds of platform movement (One-way Repeated measures ANOVA was ran) 119

Table 7.1: Non-parametric and frequency order test from Normal Foot Position of All groups 124

Table 7.2: Non-parametric and frequency order test from Turnout Foot Position of All groups 125

Table 7.3: non-parametric and Frequency order test from Normal Foot Position of Dancer group 128

Table 7.4: non-parametric and Frequency order test from Turnout Foot Position of Dancer group 131

Table 7.5: non-parametric and Frequency order test from Normal Foot Position of Gymnast group 132

Table 7.6: non-parametric and Frequency order test from Turnout Foot Position of Gymnast group 134

Table 8.1: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst All Torques and Main Axis Torques between Dancer and Gymnast groups 142

Table 8.2: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst all torques and main axis torques between Normal and Turnout positions 143

Table 8.3: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement... 145

Table 8.4: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and Total speeds of platform 146

Table 8.5: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques between Normal and Turnout positions based on separated groups 148

Table 8.6: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement based on separated Dancer and Gymnast groups 150

Table 8.7: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds of platform based on separated groups 152

Table 8.8: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement of Normal foot position based on separated Dancer and Gymnast groups 153

Table 8.9: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds platform movement in Turnout foot position based on separated groups 155

Table 8.10: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst All Torques and main axis torques in four directions of platform movement of Turnout foot position based on separated Dancer and Gymnast groups 157

Table 8.11: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds platform movement in Turnout foot position based on separated groups 159

Table 8.12: Mean and SD (Standard Deviation) values of Torque responses amongst All torques and Main axis with Turnout foot position in Forward direction at Slow platform movement (Independent samples T test was used) 161

Table 8.13: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Normal Foot × Backward' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 162

Table 8.14: Mean, SD (Standard Deviation) and SE values of joint torque responses in Normal Foot × Lateral' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 163

Table 8.15: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Normal Foot × Medial' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 164

Table 8.16: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Forward' 'between the groups (Main axis depending on the platform movement and faster means & group are in bold) 165

Table 8.17: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Backward' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 166

Table 8.18: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Lateral' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 167

Table 8.19: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Medial' between the groups (Main axis depending on the platform movement and faster means & group are in bold) 168

Table 9.1: Means and SE (Standard Error) of Standard Deviations about the X (ML) axis (SD_X) from COP (Sig. < 0.05) 176

Table 9.2: Means and SE (Standard Error) of Standard Deviations about the Y (AP) axis (SD_Y) from COP (Sig. < 0.05) 177

Table 9.3: Means and SE (Standard Error) of Range about the X (ML) axis ($Range_X$) from COP (Sig. < 0.05) 179

Table 9.4: Means and SE (Standard Error) of Range about the Y (AP) axis ($Range_y$) from COP (Sig. < 0.05) 180

Table 9.5: Means and SE (Standard Error) of from Sway Path (Sig. < 0.05) 181

Table 9.6: Means and SE (Standard Error) of ApEn (Sig. < 0.05) 184

Table 9.7: Means and SE (Standard Error) of DFA (Sig. < 0.05) 187

Table 10.1: The general orders of EMG latencies and Torque responses depending on directions of platform movement (combined foot positions) 201

CHAPTER 1

INTRODUCTION

1.1. Area of study

Many ballet studies have been realised in the area of sports biomechanics. In order to dance classic ballet, dancers need to harmoniously control their body by combining muscular power, flexibility and sensory systems. As a consequence of this, ballet is commonly considered as the basis of many kinds of dance. Dancers and some athletes in specific sports events, such as gymnastics, figure skating and synchronised swimming, train ballet not only to have basic skills but also to build better physical attributes such as flexibility, equilibrium, good balance and posture.

However, as an art, it might be difficult to evaluate dance in an objective way as positions in dance are comprised of movements, lines and postures. Thus, analysis of movements through biomechanics is necessary to understand and quantify how dancers transition from one posture to the next posture and to understand the dynamics of movement (Gretchen, 1989). Accordingly, research into ballet position, movements and techniques will help in the advancement of other diverse forms of dance, and will be useful in understanding techniques in some other sports performance as well.

The area of the science of biomechanics is description, assessment and analysis with numbers and mechanics, quantitative assessment of body movement and the main goals of studying dance can be to improve performance, prevent injuries and correct a dysfunction or weakness (Brink, 1991/92). According to Winter (1979), biomechanics analysis may be divided into 5 main categories: *anthropometry*, *muscle and joint biomechanics*, *neural control (electromyography)*, *kinetics,* and *kinematics*, all of which are interdependent.

Moreover, Brink (1991/92) mentioned that these components are important to dance studies. *Anthropometry*, which researches into physical characteristics of the body (e.g. location of Centre of Mass (COM), centres of rotation, moments of inertia), may

help dancers to understand which kind of dance is more appropriate for their physical characteristics. Also, talent identification of dancers, such as for ballet or modern dance, uses anthropometric analysis of body types and this can be improved through more quantitative biomechanical measures. *Muscle and joint biomechanics* can be applied to studying articular flexibility of ballet dancers, such as the ability to rotate the hip joint. Active and passive ranges of movement, muscle functions and the role of the articulating surface in stabilizing joints and limiting ranges of movement is of key importance for ballet. *Neural control* refers to the muscle activity from a specific movement through the nervous system and is often measured by EMG systems that show specific muscle activations. *Kinetics* measures the internal or external forces, which cause movement. Force plates and transducers are main devices to evaluate the forces (mainly external force, very few internal force measures occur). *Kinematics* describes motion, for examples, linear and angular displacements, velocities and accelerations.

The ballerina is required to perform ballet with pointe shoes on the stage during a dance show. Yet, dancing with pointe shoes can shorten the career of the ballerina because it causes serious acute and chronic conditions (Torba and Rice, 1993), however, biomechanical researching into pointe shoes has not been an active area. This area needs to be developed to find relations between balance, control and associations with injury risk.

The initial work will focus on balance and posture control as these are key requirements to be able to perform many skills in ballet. Balance and posture control are intimately related and not independent because stability is provided by postural control. Moreover, assessing balance and posture need to be considered continuously from static balance to dynamic balance because a definition of development of postural stability is possibly a continuum which can range from initial relaxation to complex and voluntary movements (Wade and Jones, 1997).

The human form is unstable by nature and if there is no continuatively acting control system it will collapse (Winter, 1995). Moreover, the balance system can be improved through ‘balance exercises’ and an improved balance system is connected to decreasing risks of fall and injuries, and are used to treat some balance disorders

(Horak, 2006). Contrary to having ‘good balance’, deficient balance function can cause high risks of falling and injury and inconvenience of life and reduced quality of Activities of Daily Living (ADL) (Guralnik et al., 1994; Conradsson et al., 2007).

Balance is a process which is related to controlling the Centre of Mass (COM) with regard to the base of support in stationary or moving situations (Irez, 2009). Posturography refers to the study of posture which can be interpreted as a static relative position of diverse body parts with respect to each other (Visser et al., 2008). Static posturography and dynamic posturography are commonly considered as the main categories for balance studies (Furman et al., 1993). In static posturography human postural sway is characterised by various evaluation methods from COP data in the time-domain or the frequency domain (Prieto et al., 1996). Therefore, the sampling duration and frequency are important factors in posturography. In particular, it has been reported that sample durations between 20 and 30 sec can get the best test-retest reliability (Le Clair and Riach, 1996).

Dynamic posturography focuses on how the participant controls his or her balance in more complex and difficult environment, therefore, a moving platform is mainly used in dynamic posturography systems (Cappa et al., 2010). The moving platform is designed to move in multiple directions not only one direction, however, moving only in one direction has been commonly chosen in many studies (Henry et al., 1998; Allum et al., 2002; Visser et al., 2008).

Additionally, understanding the role of vision in movements is also very important as well as an explicit motive for studies on standing posture in both static condition and dynamic condition or supra-postural performance (Bardy et at., 1996; Warren et al., 1996; Stoffregen et al., 1999; Oullier et al., 2002). Therefore, the role of vision will be considered to find relations between ballet standing balance and visual function for further studies.

Visser et al. (2008) mentioned that sway usually refers to a consequence of noise and regulatory activity included in postural control loops, but it is still unclear why there is postural sway during a quiet stance and how to link changes in the potential

characteristics of sway with a deficiency in balance. There is actually little scientific agreement on what is represented by sway.

In biomechanics, the COP displacement is a result of the net-neuromuscular response generated by the Central Nervous System (CNS) to control the position of the COM (Winter et al., 2003). Also, the CNS controls a number of mechanical linkages through multiple muscles, as a result, the COP is eventually moved to place the COM within the BOS (Rietdyk et al., 1999). As a result, Visser et al. (2008) claimed that the aim is to minimize the displacement of the COM which can be done by adjusting the COP displacements by two mechanisms: feedforward (Gatev et al., 1999) or feedback control (Johansson et al., 1988). However, there is no real explanation to why the COM keeps moving and also whether sway helps with keeping balance ("good sway") or on the contrary is harmful to balance ("bad sway") (Visser et al., 2008).

Winter (1995; 2009) described the difference between the COM and COP and a relation with body sway at five different times of the changing situation while a subject is swaying back and forth. Through all events related to the COP and COM, it is evidenced that the net ankle moment is varied by the plantarflexors and dorsiflexors to control the COP and regulate the COM. Therefore, the COP must alternate between anterior and posterior positions of the COM, thus, the dynamic range of the COP must be greater than that of the COM. Possibly, the participant would involuntarily step forward to stop from falling frontward if the direction of ω is not changed and even if the COP tried to correct by moving to the tip toes.

The inverted pendulum is the most common simulation model for biomechanics studies of balance since it allows a simple representation of a balanced system. The inverted pendulum model allows analyses of the dynamics of balance by relating the trajectories of the COP and COM. The angular acceleration in the inverted pendulum model is determined from the position of the COP relative to that of the COM (Winter, 2009). In most studies, the inverted pendulum model is used to solve balance problems, especially with a human subject in upright quiet standing position.

While the human body maintains upright standing it sways, this balance control is controlled by the CNS using sensory feedback (Winter, 1995; O'connor and Kuo, 2009) and one of the research methods to understand balance motor control is Electromyography (EMG). Many studies have researched into EMG activation and latencies for various dynamic posturography changes. For instance, directions of platform movement (Moore et al., 1988), different speeds (slow and fast) (Horak et al.,1989) and their effects on EMG and kinetic data (joint torques) have been analysed together (Diener et al., 1988).

1.2. Statement of Purpose

The purpose of this thesis is to develop an understanding of dance balance characteristics depending on various kinds of dance, related positions and shoe types which contribute to dance performance and to understand different balance control in different groups (Dancers vs Gymnasts).

1.3. Research Questions

To achieve the purpose of this study, the following research questions will be answered.

Q1. What differences in balance performance is there in different ballet positions and shoe types using multiple balance metrics?

Balancing in dance may require dancers to have different or similar postural control skills depending on positions or shoes. One of the main analyses of balance is looking at the COP trajectory (Bloem et al., 2003; Rossi et al., 2009). COP and COM is the results of lots of neuromuscular actions and has a complex structure and applying only simple metrics may not be enough. Therefore, applying only simple balance metrics, such as range, standard deviation and sway path may not be enough to show which ballet position or shoe types allows dancers to achieve better balance. Balance is sensitive and the size of BOS is different depending on which

kinds of shoe dancers wear (e.g. smaller BOS on pointe). It is important to use other balance metrics including time series signals and compare results from many balance metrics. In order to approach this systematically it is necessary to focus on related dance positions first. Therefore, ballet 2nd positions (flat, demi-pointe and pointe) were performed wearing ballet and pointe shoes to investigate variations of balance control in ballet. Balance when standing on one leg will be interesting to compare against balance on both legs.

Q2. What are the main characteristics of balancing on Pointe shoes and do types of shoes affect balance?

The use of footwear is very important to dancers to keep their feet healthy and pain-free, therefore, footwear influences dancers' movement and foot motion and may affect injuries (Yan et al., 2011). From a comparison between barefoot and ballet shoe while standing on demi-pointe one leg, it was found that dancers had a better stability standing on barefoot because BOS became larger by spreading the toes (Costa et al., 2012). Standing on tip toes while wearing pointe shoes is challenging unless someone is well trained and skilled. Pointe shoes consist of a toe box, shank, satin body and ribbon. The toe box is very solid and the shank is hard but elastic and these are the important differences of pointe shoes compared to normal cotton or leather ballet shoes. Accordingly, it is expected that there will be different abilities of balance control between wearing ballet and pointe shoes and an important aspect of the study is to determine these differences.

Q3. Are balance strategies related to dance positions (Turnout versus Normal) and/or level of difficulty (Flat feet versus Demi-Pointe)?

Many researchers have investigated and studied normal standing balance (Winter et al., 2003; Bottaro et al., 2005) and with stimuli (Moore et al., 1988; Horak et al., 1989; Diener et al., 1988). However, there are no studies which have looked into ballet turnout position or compared it with balance from normal standing position.

Winter (1995) found balance strategies between frontal plane (medial/lateral) and sagittal plane (anterior/posterior) models in which the frontal plane model uses a parallelogram pivoting about both ankle and both hip joints and the sagittal plane model pivots about the ankle in quiet stance, or about both hip and ankle in perturbed standing. As the parallel feet position (the same as the normal standing) is used in contemporary dance and the dancer needs to keep the turnout position while dancing ballet, these positions will be compared to see if balance strategies may be different or similar while standing with and without platform movements (external stimuli). Additionally, the balance strategies can vary also depending on difficulties of the dance position (flat feet and demi-pointe) as there are differences of BOS size and degree of freedom between flat feet and demi-pointe positions. The demi-pointe position is considered to be more difficult to maintain balance. Therefore, comparisons of these variations will help to understand strategies and mechanism of dance balance.

Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

One leg standing in dance positions incurs greater difficulties in maintaining balance and requires dancers to work harder to keep their balance. This is due to the smaller base of support (BOS) and reduced amount of somatosensory feedback. Many balance strategies while standing on double legs have been found and discussed in number of research studies (Jian et al., 1993; Winter, 1995; Rietdyk et al, 1999; Winter, 2009). Balancing on single leg in dance has been studied by Costa et al. (2012). However, this study only looked into a single leg balance for different poses effects and shoe conditions effects. There is no study comparing standing on single leg and standing on double legs depending on turnout and parallel feet positions. Standing on one leg may have different aspects of balance strategies and/or show differences on balance strategies compared to both leg standing in both turnout and parallel. There may also be differences in balance strategies or mechanism from these various conditions between beginners and experts. The dance positions should probably be limited to those used in performances such as lifting the thigh of the non-standing leg up to the pelvis (90° to the body) in the same way as dance

positions during turning (in each direction of side, turnout - ballet, and front, parallel - contemporary dance, with the bent knee and the foot pointed toward to the knee).

Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

There are complicated interactions and time delays that relate to neurological response and mechanical response in the control of human balance. To examine responses in balance control, applying external perturbations to the human body during standing may enable us to understand balance strategies including both neurological and mechanical aspects. It is expected to have differing results depending on slow or fast external perturbation. Results might also be related to the dance positions (e.g. 'turnout verse parallel', 'flat feet verse demi-pointe', 'standing on both legs verse 'standing on one leg').

Q6. What are the differences in balance control between Dancers and Gymnasts?

Accuracy and coordination of balance control in dance or gymnastics varies depending on individuals and their levels, even if they are performing the same movement and they are trained to balance as part of their activity.

According to Shumway-Cook and Woollacott (1985), when children begin to be able to do postural responses to changing sensory conditions they learn to shift the dominant sensory inputs through using visual and/or somatosensory inputs. Seven to ten years old children show increased balance abilities compared to the younger children's group, for example, shorter response latencies and even developed balance control reached to adult levels.

To understand differences in balance control strategies based on balance skills, studying balance in various groups is helpful to develop balance skills in any sports

or dance which requires good balance skills. Especially, both dancers and gymnasts have good balance skills but they might have different balance control in some cases.

CHAPTER 2

REVIEW OF LITERATURE

2.1. Balance and Posture Control

It is a well-known fact that having good balance and postural control systems helps our ability to stand and walk during daily activities of our everyday life (Horak, 2006; Conradsson et al., 2007). The basic meaning of balance is defined by Winter (1995) as: “Balance is a generic term describing the dynamics of body posture to prevent falling. It is related to the inertial forces acting on the body and the inertial characteristics of body segments.” Moreover, posture is described as “The orientation of any body segment relative to the gravitational vector. It is an angular measure from the vertical.”

Yet, other scientists have various views about balance and posture. Williams (1983) separates balance into static and dynamic balances and these have been measured differently, such as standing positions of individuals for static balance or moving and changing position for dynamic balance. Furthermore, Wade and Jones (1997) think that assessing balance and posture need to be considered continuously from static balance to dynamic balance because a definition of development of postural stability is possibly a continuum which can range from initial relaxation to complex and voluntary movements. This view focuses on ‘what is sometimes called static balance from dynamic balance’.

Balance is a process that controls the COM location with regard to the base of support in both stationary and dynamic situations (Irez, 2009). The ability of keeping or returning the COM over the base of support to maintain equilibrium in a gravitational field is called postural control and if humans are not supported while they are standing, they will lose their stable equilibrium or balance. To regain the stable condition, the force of gravity should be opposed by forces from muscles (Horak, 1987). There are some difficulties of measuring postural control because the location of COM cannot be measured conveniently (Palmer, 1944; Murray et al.,

1967; Winter, 1979) and even though many equilibrium positions exist most of them have only a few degrees of body sway (Hayes, 1982).

When preparing to start a movement from stationary, or during the preparatory movements, such as rising from sitting to standing, stability as a form of balance is provided by postural control which means that balance and posture control are intimately related and not independent (Wade and Jones, 1997). Furthermore, balance and posture control are inseparably combined in most movements and it is possible that adequate balance might not be promptly occurred from one task to other tasks (Moe-Nilssen and Helbostad, 2002).

Winter (1995) mentioned that due to distribution of human body mass as a biped, the balance control system is naturally unstable if there is not a continuously acting control system. Therefore, human's balance system is related to locomotion with 'one foot', 'no feet' or 'both feet' contacts over the ground. There are many examples of human locomotion, for instance, while human is running and hopping, no feet or one foot is in contact at a time. During walking, there is a need for one foot or two feet to be in contact. Too-footed contact moves occur in some sports situations such as shifts, jumps and landings. Additionally, standing, where there are both feet in contact as in many daily activities, commonly occurs in dance movements along with one foot standing. These different situations of foot contacts happen in various sports and dance depending on movements and situations.

According to Horak (2006) 'balance exercises' help to improve 'the balance system' of patients, who have balance problems, and it may result in decreasing risks of falls and injuries. 'Balance exercises' are also used as treatments for balance disorders. Moreover, high quality of Activities of Daily Living (ADL) can reduce balance problem (Guralnik et al., 1994).

Carr mentioned that (2004) balance requires coordination and control, therefore, good athletes with great balance during their performance can control perturbing forces and retain balance while they are performing. Athletes should be able to keep their balance during both static and dynamic movements, for instance handstand in

gymnastics and running back for a try in rugby. Athletes tend to possess good balance skills even if they are in different situations.

In most research, the posture studied is ‘natural’ upright standing. However, humans tend to attempt “unusual” postures, in many sports for example. The study of these postures increases the understanding of athletic performance and the nature of visual-postural regulation in the human body (Gautier et al., 2007). To organise the standing postural regulation, the body uses a three-level hierarchical system starting from the ankles to the hips and then the knees (Nashner and McCollum, 1985).

Riccio and Stffregen (1998) demonstrated that there are 2 types of regulations for human’s standing posture: first of all, the regulation is automatic and is achieved in the robust region. The other one consists in redefining new appropriate automatic strategies from the ones arising from the robust region. This is achieved in the adaptive region.

2.2. Static and Dynamic Posturography

Visser et al. (2008) explained that posturography refers to the study of posture which can be interpreted as a static relative position of diverse body parts with respect to each other. Commonly, to investigate the active and passive regulation of balance, various posturography techniques have been widely used in diverse conditions. Abilities to evaluate responses of participants and controlling actively posture or balance are included in principal elements of most posturography techniques.

To analyse posturography and gait, analysing the reaction forces between the feet and surface is one of the important tools and a common method (Rossi et al., 2010). Also, if postural asymmetries are found, these may be due to orthopaedic disorders or sensory feedback problems (Visser et al., 2008). Therefore, characterisations of these problems and efficiency of rehabilitation treatment can be quantitatively evaluated by posturography (Minshew et al., 2004; Pozzo et al., 2006). In some cases, the treatment result can be improved by a precise evaluation from posturography of the effectiveness of the therapy (Visser et al., 2008).

To measure posturography, postural responses are collected by measures for quantitative analysis. Moreover, kinetic measures (the causes of movement; related to momentum, inertia, mass, weight and force), kinematic (actual movements of body segments) and EMG are included in posturography measurements and detailed information of equipment and outcome measures are shown in Figure 2.1 (Bloem et al., 2003). The standard measuring instruments for the Ground Reaction Force (GRF) and COP, in both static and dynamic posturography, are the force plate and pressure sensors (in shoe insoles or flat sheet of sensors applied on a rigid surface) (Rossi et al., 2010).

The analysis of the GRF and COP trajectory generated by the body sway is the basis of all studies of balance and posture (Bloem et al., 2003). By studying the information gathered from the data we can analyse the postural control of the subject and use the result of this analysis to assess the recovery or progression of a pathological condition (Rossi et al., 2010). Typical parameters to measure COP are ‘root-mean-square’ and ‘range of variation’, ‘mean and median frequencies’, ‘sway

area' and 'mean velocity' (Prieto et al., 1996). However, these are reliable only if the COP position is accurately determined.

Table 2.1: Recording equipment and outcome measures depending on types of modality in posturography (Bloem et al, 2003)

Modality	Recording equipment	Outcome measure
Kinetics	Force plates	Centre of pressure Torques Shear forces and moments
Kinematics	Motion sensors	Centre of gravity Segment motion
	Optical motion analysis	3D spatial representation of body (parts) in time
Electromyography	Surface electrodes	Background muscle activity
	Needle electrodes	Individual postural responses
	Inserted wire electrodes	Postural synergies

Commonly, static posturography and dynamic posturography are considered as the main categories and one of these can be allocated as a specific posturography technique (Furman et al., 1993). Static posturography is used for evaluating postural control when the participant is standing while keeping a quite unperturbed position, for instance quiet standing on a non-moving fixed surface (Visser et al., 2008; Rossi et al., 2010). Yet, effects from gravity and some corrective movements caused by the participant need to be taken into account since these might alter the static stance which is supposed to be, for example, a quiet and unperturbed standing (Kuo et al., 1998; Creath et al., 2002).

In static posturography, human postural sway is characterised by various evaluation methods from COP data in the time-domain or the frequency-domain (Prieto et al, 1996). Therefore, the sampling duration and frequency are important factors to measure posturography and sampling time durations, trial lengths, can be applied

from a few seconds to 30 min in various static posturography studies (Visser et al, 2008). Also, it has been demonstrated that the sampling duration clearly affects the descriptive measures in both time and frequency domains (Carpenter et al., 2001; Le Clair and Riach, 1996). In particular, it has been reported that sample durations between 20 and 30 sec can get the best test-retest reliability (Le Clair and Riach, 1996). Some aspects of postural sway can be observed with a longer period duration of standing whereas they would go unnoticed with a shorter sample period (Duarte and Zatsiorsky, 2000) as a longer sample duration allows to correctly represent in descriptive measures the large amplitude/ low frequency components of the COP (Carpenter et al., 2001). In addition, testing eyes closed or eyes opened while doing quiet standing is a common static posturography in several studies.

Dynamic posturography is different to static posturography because it focuses on how the participant controls his or her balance in more complex and difficult environment; therefore, a moving platform is mainly used in dynamic posturography systems (Cappa et al., 2010). By imposing ground movement perturbations through a passive or motorised platform, the equilibrium control ability of the subject can be analysed with determining its limitations of postural stability (Browne and O'Hare, 2000; Ionescu et al., 2006; Furman, 1994; Furman, 1995).

The moving platform is designed to move in multiple directions and rotations, not only one direction (Henry et al., 1998; Allum et al., 2002), however, moving only in one direction (or 2 directions) has been commonly chosen in many studies in the past. Also, there are various conditions of platform movements for dynamic posturography such as controlling speed (slow & fast), amplitude (small & large) (Diener at al., 1988), prediction (predictable & non-predictable, pseudorandom) direction (directional & unidirectional) (Moore et al., 1988; Allum and Honegger, 1998) and rotation (dorsi-flexion & plantar-flexion).

More detailed conditions and types of physical perturbations are shown in Table 2.2 which dynamic posturography involves (Bloem et al., 2003).

Table 2.2: External and Self-inflicted perturbations in dynamic posturography (Bloem et al., 2003)

External perturbations
▪ Moving support surface - Translation, rotation or vertical displacement - Unidirectional vs multidirectional - Abrupt vs continuous (e.g. sinusoidal) - Predictable vs non-predictable stimuli ▪ Stimuli applied to upper body parts - Hips - Trunk - Head
Self-inflicted perturbations
▪ Voluntary weight shifts ▪ Anticipatory postural responses ▪ Balancing on unstable support surface

According to Visser et al., (2008) when using a moving platform for dynamic posturography studies, the acceleration of the platform defines the true mechanical perturbation not the velocity or displacement of the platform. In a study, it should be considered that after its first acceleration, the platform needs to decelerate before reaching the end of its maximum excursion. It is possible that this phenomenon may cause misinterpretation of posturography data. Indeed, the stroke of the platform is usually limited to centimetres in a laboratory environment which means that the interval between acceleration and deceleration is short. Therefore, there could be interferences between reactive postural responses during acceleration and postural responses during deceleration (McIlroy and Maki, 1994).

The measured COP, joint torque and body sway are especially affected by these interferences (Visser et al., 2008). Also, the non-muscular forces created due to balance disturbance (e.g. the platform deceleration) may enhance the subject's ability to restore balance using muscular forces (Bothner and Jensen, 2001). The deceleration might stop the effect of the previous acceleration and change the direction of it, therefore, the subject can stabilise more easily (Van Asseldonk et al.,

2007). This limitation needs to be considered in all studies using a moving plate or platform and is therefore a limit to the ecological validity of results (Visser et al., 2008).

Rossi et al. (2010) emphasised that the sources of measurement errors in the COP mainly come from the force plate accuracy which is caused by the electrical bias such as amplifier, low frequency noise and conditioning unit drift according to many previous researches. Due to these, the position inaccuracy of the COP can range from ±20 mm or ±30 mm (Bobber and Schamhardt, 1990; Schmiedmayer et al, 1999; Kim et al, 2007). To minimise inaccuracy of the COP, measuring instrumentations need to be calibrated and several methods exist to calibrate force plates (Rossi, et al., 2010). A simple one consists in applying vertical loads in various and known locations of plates in order to determine a correction formula to reduce the COP error (Collins et al., 2009).

Rossi et al. (2010) explained that the inertia effects generated by the moving plate cause another source of inaccuracy in dynamic posturography and also mentioned about two strategies to reduce this inaccuracy were highlighted in some literatures:
(a) It is important to analyse force data at the end of the platform translational perturbation because the data at the beginning of the platform translation contains passive and reflex contributions and these information should be ignored in data analysis (Bhatt et al, 2006; Carpenter et al, 1999; Henry et al, 2001).

(b) Inertial effects can be found and corrected by using numerical algorithms and force transducers, for example, an accelerometer cluster (Pagnacco et al, 2000), a force platform (plate) (Preuss and Fung, 2004) or a motion analysis system (Preuss and Fung, 2004; Yang and Pai, 2007).

2.3. Understanding Stability and Body Sway

2.3.1. Stability and Body sway

Stability is a very important ability for human. Fitt (1988) explained that any human movement requires fighting against gravity, and this is also the case for maintaining stability. Indeed, staying stable in a position is as important as ensuring a movement through time and space and is the basis of all potential movement. In fact, a stable position is of significant importance to ensure an effective human movement and is usually obtained by countering actions from gravity and even from other muscles.

Carr (2004) mentioned that stability is the amount of resistance a subject opposes to a perturbation in order to keep their balance undisturbed. In some cases an athlete can be in a balanced position and very stable at the same time while in other situations an athlete can be very unstable even in a balanced position. For example, a Sumo wrestler standing low on the ground is obviously more stable than a ballerina turning on toes even though both of them are in balanced positions.

According to Gibson (1966), movement and perception are closely related: humans use their perception before moving and, also, modify this perception through their movements. Besides, Gibson also pointed out the paradox of stabilised posture: controlling the stability of a posture requires a minimum of movement. As an example, when humans are standing quietly, their own bodies move to keep the stabilised standing posture.

It has been demonstrated in fact that humans can shift their COP on the support surface voluntarily (Latash et al., 2003) and with the help of biofeedback protocols, reducing the sway size (Hamman et al., 1992; Dault et al., 2003). However, as mentioned before, there is no real explanation to why the COM keeps moving and also whether sway helps keeping the balance (“good sway”) or on the contrary is harmful to the balance (“bad sway”) (Visser et al., 2008).

2.3.2. Linear Stability

Carr (2004) explained that the term linear stability refers to two kinds of situations, one is the amount of resistance a subject can oppose before being moved and the other one is the amount of resistance to apply in order to stop or change the direction of a subject in a displacement. Linear stability is therefore a function of the mass of the subject which can be moved linearly. The heavier a subject the more force is required to alter its movement. Athletes, depending on the skills required, will look for a higher linear stability (e.g. Sumo wrestler, Judoist) or a lower one (e.g. Ballerina). In some cases, stability is also related to friction, the higher the friction between a body and the surface of contact the higher this body's stability.

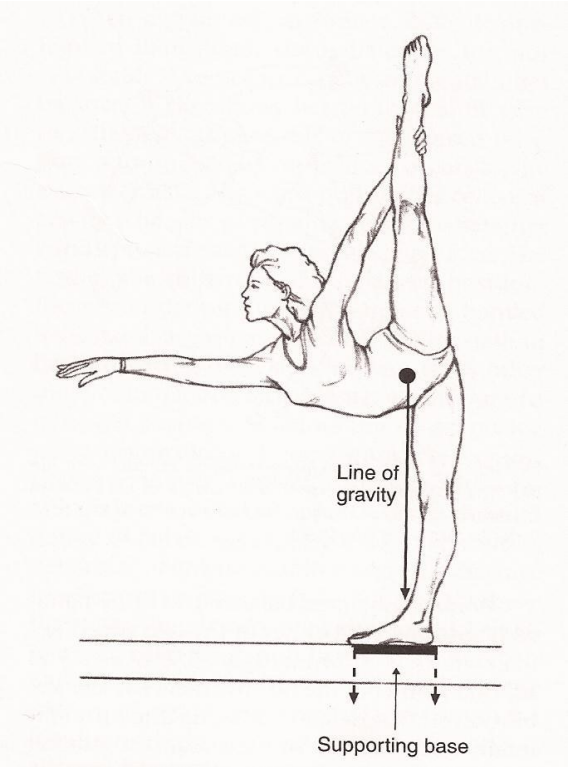


Figure 2.1: The gymnast is standing on the beam. Supporting base (BOS) is the contact area between the foot and the beam and the line of gravity falls within it

2.3.3 Rotary Stability

Stability can be moved rotationally too. According to Carr (2004) rotary stability can be described as the ability for an athlete to keep his or her balance while rotating. However, a destabilizing torque resulting from external forces like gravity, resistance, other bodies, air movement or a combination of these can upset the balance of the athlete.

Figure 2.2: The ballerina is performing arabesque and standing on foot (Dance net, 2008)

Therefore, good athletes who can perform their movements with an excellent rotary stability can resist the opposing turning effect of this torque, which will then have to be higher to upset the balance. Once a torque has been applied against athletes through the previously cited external force, any parts of the body can become an axis for rotation. Also the rotation can be made by contacting with a solid surface, for instance, the axis can be positioned on the ball or the foot in contact with the ground in ballet when a ballerina performs a pirouette.

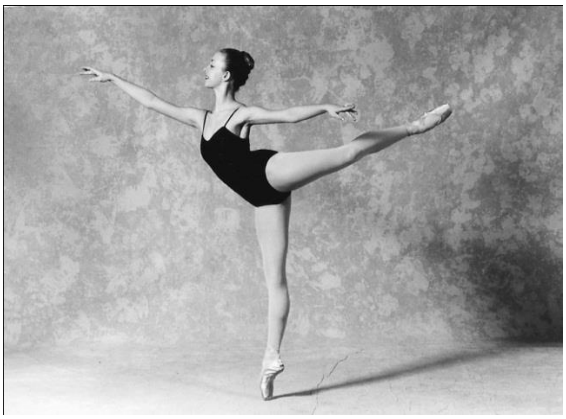


Figure 2.3: Arabesque balance on tip toes with pointe shoes (Klein, 2011)

To increase rotary stability, it is helpful to widen the Base of Support (BOS), since the line of gravity needs to be within the BOS. The location of the Centre of Gravity (COG) should be low, also having more weight is better and the BOS has to become wider in the same direction as the direction of force (Carr, 2004). It is necessary for balance that the COM stays within the BOS, or at least stays between the two feet for running and single-support walking since in this case the COM will be outside the BOS (Winter, 2009).

Some examples of BOS are shown from Figure 2.1 to Figure 2.3. In the Figure 2.1 picture, the gymnast is keeping her balance on the beam. Here, the area of BOS is located under her right foot which contacts on the beam and a line of gravity from COG falls within the area (Carr, 2004). It is described how the gymnast can control the balance when she is standing on the beam on one foot while she is performing a movement which is similar to ballet arabesque. Compared with the gymnast's picture, ballet arabesque also has a BOS of a size similar to the size of the foot (Figure 2.2). However, the area can be decreased when a ballerina performs arabesque on the toe with pointe shoe (Figure 2.3). Owing to the toe box, the supporting base is reduced and the location of the COM seems to be placed in higher part of body compared with wearing normal ballet shoes. Moreover, balancing above a very small BOS makes it difficult for the athlete to maintain the

balance against shifts of the COG (Carr, 2004). Therefore, this principle is applied in ballet balance and it is assumed that the ballerina will have more difficulties to keep her balance with the pointe shoes than with the normal ballet shoes.

Furthermore, the size of BOS can be different depending on positions in dance and, also, it is related to stability in dance movements. Therefore, not merely balance but also stability need to be considered as well for dance researches by perturbing their balance.

2.4. Centre of Pressure and Centre of Mass

2.4.1. Definition of the COP and COM

To test balance, the most common method is to quantitatively assess postural sway with force plates (Burl et al., 1992). Many investigators and even in many areas have argued about assessing COM and COP in balance and postural control studies and measuring of these have been confused (Tanaka et al., 1999; Winter, 2009).

Winter (1995) defines the COM as “a point equivalent of the total body mass in the Global Reference System (GRS) and is the weighted average of the COM of each body segment in 3D space, this is a passive variable controlled by the balance control system”. Additionally, the location of the vertical projection of COM onto the ground is often considered as the COG. According to Winter, the COP is described as “the point location of the vertical ground reaction force vector” and “It represents a weighted average of all the pressures over the surface of the area in contact with the ground”. Also, COP and COM trajectories are independent, for instance, if one foot or both feet contact on the ground, net COP lies within that foot or somewhere between the two feet respectively, depending on the relative weight loaded by each foot.

According to Winter (2009), therefore, the COM and COP’s trajectories can be compared through the trajectory of the vertical line between the COM and the surface. The location of the vertical GRF vector from a force plate is located in the trajectory of COP, which is not equivalent to COM (but these can be related), and it can be considered that all body contact points are on the platform. Moreover, downward forces to the force platform are affected by the foot placement and the ankle muscles’ motor control. Also, moving hands up and down only alter vertical forces. Therefore, the COP should not be referred as ‘sway’ and the horizontal position of the COM is the accurate way to find out ‘sway’ but COP is commonly used and has been shown to be a easily measured and viable alternative.

2.4.2. Centre of Pressure on the Foot

Caldwell et al. (2004) explained about COP on the foot. After calculating the COP with x and y axes in the Global Coordinate System (GCS), a relationship between the location of the COP and the position of the participant can be investigated. The COP location over the surface changes with a humans' movement, such as walking, running and both feet in contact, as they using different points of contact with the ground or the same contact points but different positions of the body above those contact points. For instance, when standing on one foot on the plate, the COP is located inside of the area between the platform and the foot or shoe in contact with it. Then the COP moves following a pattern going from the heel to the toes during walking (Cavanagh, 1978).

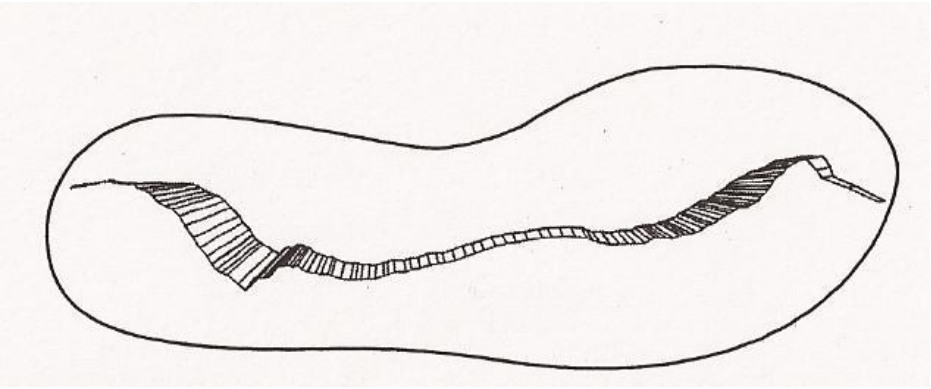


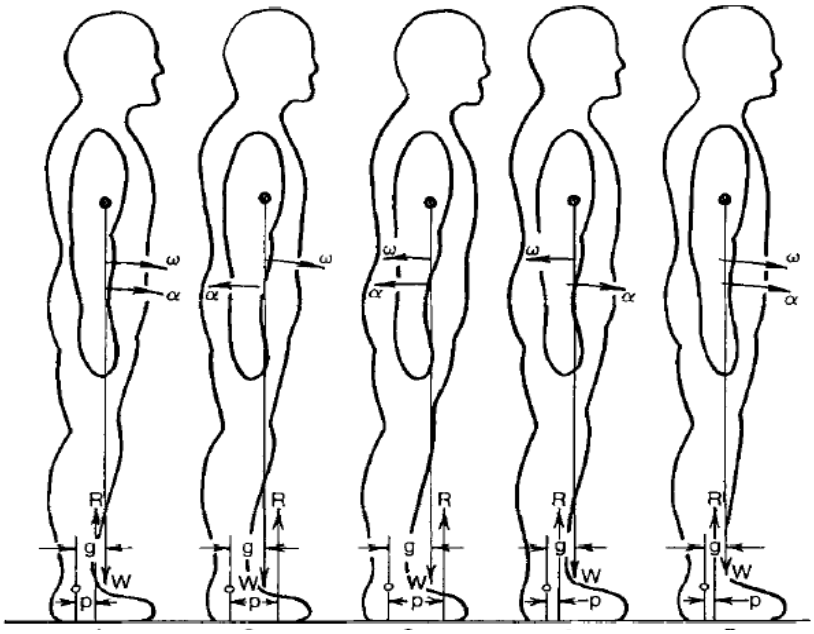
Figure 2.4: The foot print with COP path. Directions of force vectors are shown in the transverse plane by line segments and path of COP is the closest line to medial side of foot (Caldwell et al, 2004)

Caldwell et al. (2004) also explained about COP path with a COP path related to a foot print (Figure 2.4) which was firstly presented by Cavanagh (1978). The foot picture depicts a relationship between a way of averaging COP paths and the outside edges of the foot or shoe in human's gait during walking. Directions of force vector are indicated through numbers of vertical lines inside of the transverse lines and the COP path is shown by the transverse lines closest to the medial side of the foot.

2.4.3. Differences Between the COM and COP During Quite Standing

Rietdyk et al. (1999) explained about the relationship and differences between the COM and COP. The Central Nervous System (CNS) controls a number of mechanical linkages through multiple muscles; as a result, the COP is eventually moved to place the COM within the BOS. Therefore, controlling balance requires to systematically control the COM, which must stay within the boundaries of the BOS while performing a quiet standing. Researchers, after studying the inverted pendulum on upright posture, stated that the COM acceleration is derived from the COP displacement (Jian et al., 1993; Winter, 2009). The horizontal acceleration of the COM during quiet standing is related to the difference between COM and COP (Winter et al., 1998). Also this difference shows during normal walking initiation and termination (Jian et al., 1993).

The difference between the COM and COP and a relation with body sway have been discussed and these are shown in Figure 2.5 by Winter (1995; 2009). A subject is swaying forward and backward while he or she is standing on a force plate and five different points of the changing situation are depicted in time. Firstly, in Time 1, the



(g) Distance associated with Centre of gravity

(p) Distance associated with Centre of pressure

(α) Locations along with the associated angular accelerations

(ω) Angular velocities

(w) Vertical body weight vector

(R) Vertical ground reaction

Figure 2.5: A subject sways the body back and forth while standing quietly on a force plate (adapted from Winter, 1995; Winter, 2009)

vertical line of the COM is located just in front of the COP because the ‘parallelogram of forces’ affects each distance of ‘g’ (between the ankle joint centre and Vertical body weight vector) and ‘p’ (between the ankle joint centre and location of Vertical ground reaction) from the ankle joint. Furthermore, the body of the participant will have a clockwise angular acceleration because the value of the clockwise moment Wg is higher than Rp which is the anticlockwise moment. In Time 2, the vertical way of the COM is pointed in COP and the position of COM is influenced by increasing the plantarflexor activity to correct the forward imbalance that happened in Time 1. Therefore, α is keeping the posterior direction and starting to reduce ω until Time 3 and then from Time 3, ω and α become anticlockwise and manifest a backward sway. At Time 4, the participant decreases the planterflexor activity to reduce the range of the COP as a response to the backward sway. From now on, Wg becomes higher than Rp and the direction of α changes to forward and then after a while, ω decreases and reverses its direction to forward as well. Once these processes are finished, the original conditions come back same to original (Time 5).

According to Winter (1995; 2009), through all events related to the COP and COM, it is evidence that the net ankle moment is varied by the plantarflexors and dorsiflexors to control the COP and regulate the COM. Therefore the COP must alternate between positions anterior and posterior to the COM. Thus, the dynamic range of the COP must be greater than that of the COM. Possibly, the participant would involuntarily step forward to stop from falling frontward if the direction of ω is not changed and even if the COP tried to correct it by moving onto tip toes.

2.4.4. Measuring Balance Control in Both Feet - COP_{net}

The case described previously with Figure 2.5 is a special case of a more general approach. According to Winter et al. (1995), in a side-by-side standing position, it is not possible to know if both feet are having the same contribution in balance control in a symmetrical and unilateral way. By using two force plates, the independent left and right controls at the ankles as well as a separate balance control in the M/L direction can be observed. The combined control of right and left dorsiflexor/plantaflexor is called COP_{net} and this one, in A/P or M/L directions is calculated in the following way:

$$\mathrm{COP_{net}} = \mathrm{COP_l}\frac{\mathrm{R_{vl}}}{\mathrm{R_{vl}+R_{vr}}} + \mathrm{COP_r}\frac{\mathrm{R_{vr}}}{\mathrm{R_{vl}+R_{vr}}} \quad \textbf{(1)}$$

Where:

COP_l and COP_r are the COPs under respectively the left and right feet

R_{vl} and R_{vr} are the reaction forces acting respectively on the left and right feet

In the M/L direction, the left ankle invertors/evertors control COP_l while the right ankle invertors/evertors control COP_r. The time-varying fraction function of the loadings under each foot $\frac{\mathrm{R_{vl}}}{\mathrm{R_{vl}+R_{vr}}}$ or $\frac{\mathrm{R_{vr}}}{\mathrm{R_{vl}+R_{vr}}}$ represents the dynamic load changes under each foot. These dynamic load changes are unphased and acting in opposite way: increasing the load in one limb will unload, at the same time, the other limb. Increasing or decreasing the activity in the hip abductor/adductors causes the variations in dynamic load. If it is assumed that the hip abductor and adductor have no influence in the dynamic loading (then the load/unload mechanism is not active) the following can be written:

$$\frac{\mathrm{R_{vl}}}{\mathrm{R_{vl}+R_{vr}}} = \frac{\mathrm{R_{vr}}}{\mathrm{R_{vl}+R_{vr}}} = 0.5 \quad \textbf{(2)}$$

2.4.5. Inverted Pendulum Model

Winter (2009) described the inverted pendulum model. Safe posture and balance is a necessity in all daily activities from home to work and especially in sports. The Inverted Pendulum Model allows analysing the dynamics of balance by relating the trajectories of the COP and COM. As mentioned before in Section 4.3 'Why the COM and COP are difference during quite standing', the angular acceleration in the inverted pendulum model is determined from the position of the COP relative to the one of the COM. The inverted pendulum model has been applied in a biomechanical analysis in sagittal and frontal planes by Winter et al. (1998).

According to Winter (2009), the balance equation obtained in the sagittal plane, and assuming a body sway at the ankles, is the following:

$$\mathrm{COP_x} - \mathrm{COM_x} = -\frac{\mathrm{I_s C\ddot{O}M_x}}{\mathrm{Wh}} \quad \textbf{(3)}$$

The balance equation in the frontal plane is mostly similar:

$$\mathrm{COP_z} - \mathrm{COM_z} = -\frac{\mathrm{I_f C\ddot{O}M_z}}{\mathrm{Wh}} \quad \textbf{(4)}$$

Between the two balance equations (1) and (2), the main difference is the muscle group controlling the COP.

- In equation (1): $\mathrm{COP_x} = \mathrm{M_a/R}$, where:

  M_a is the sum of the right and left plantorflexor moments

  R is the total vertical reaction force at the ankles

- In Equation (2), $\mathrm{COP_z} = \mathrm{M_t/R}$, where:

  $M_t = M_{al} + M_{ar} + M_{hl} + M_{hr}.M_{al}$ *with M_{ar} and M_{al} the left and right frontal ankle moments and M_{hl} and M_{hr} the left and right frontal plane hip moments*

Therefore, four torque motors, one at each corner of the parallelogram formed by the two lower limbs and the pelvis, control the frontal plane balance. It has been shown that the hip abductor/adductor moments have a major role in the control of balance

in side-by-side standing (Winter et al., 1996) while the ankle invertor/evertor moments have a low influence in the control of balance. Equations (1) and (2) are evidence of the validity of the inverted pendulum model and since measures of COP and COM are independent, the COP-COM correlation with COM measures the validity of the model.

Studies using the inverted pendulum model of upright posture state that the acceleration of the COM is determined by the displacement of the COP (Jian et al, 1993; Winter, 2009). Assuming that the body acts as a single inverted pendulum during quiet standing allows developing the original inverted pendulum model and the COP-COM strategies mentioned previously (Winter et al., 1998; Rietdyk et al., 1999).

Rietdyk (1999) explained that before describing the response strategies in terms of COP-COM control, the model must be validated for the observed trunk observations. The kinetic strategies considered to move the COM should be defined as that all joints will contribute to the recovery, but not equally, and these different contributions will depend on where the perturbation acts (shoulder versus pelvis) (Rietdyk et al., 1999).

2.4.5.1. M/L and A/P Models

It has been demonstrated (Winter et al., 1995) that the load/unload mechanism is the major control in the M/L direction, whereas the ankle muscle control of COP_r and COP_l has less influence. Figure 2.6 below is an example of a simple inverted pendulum model. In the frontal plane (M/L model), the pendulum, with a parallelogram shape, pivots on both ankles and hips and is controlled by a set of four muscles. In the sagittal plane (A/P model), the pendulum pivots on the ankles in quiet standing and about the hips in perturbed standing.

According to Winter (1995), the ankle and hip joints can act as two control sites and this model has the COM of the lower limbs in the A/P model. The locations of the COM are similar in the M/L model with two joints at ankles and hips as possible control sites. As a result, the parallelogram delimited by the ankle and hip joints is controlled by four torque motors. The activations of the ankles evertors/invertors and hips adductors/abductors can cause the COP_{net} to move. As an example, a movement of the COP_{net} to the right could be caused either by activating the left ankle evertors, right ankle invertors, left hip adductors or right hip abductors and would result in an acceleration of the COM to the left. The magnitude of the torque acting at each joint depends of the biomechanics and anatomy of the joints at ankle and hip and therefore cannot be the same. In the A/P model, the right and left dorsiflexors and plantaflexors work in synchronization to move back and forth the COP under each foot to control balance. In the M/L model however, any action from the evertors/invertors will make the COP move under each feet in the medial and lateral direction.

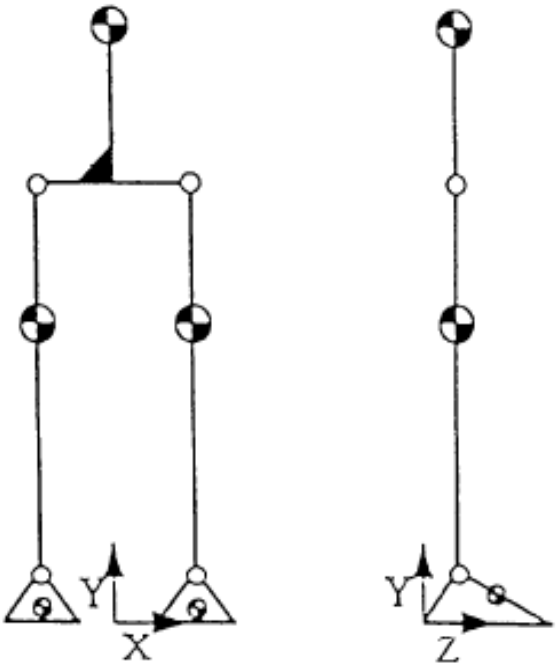


Figure 2.6: Standing inverted pendulum biomechanical models. The frontal plane pendulum model is a parallelogram pivoting about both ankle and both hip joints. Also, this model is under the control of four sets of muscles. The sagittal plane model pivots about the ankle in quiet stance or about both hip and ankle in perturbed standing (Winter, 1995).

2.5. Neurological Control During Balance

Continuous balance control against instabilities is controlled by the CNS (Centre Nervous System) using integrative sensory feedback such as somatosensory, visual, vestibular sensors (Winter, 1995; O'connor & Kuo, 2009) and other sensory inputs such as haptic, joint angle and torque (Horak & Macpherson, 1996). A typical view of the main sensory system is that the body relies on somatosensory sensor (70%) more than vestibular (20%) and vision (10%) sensors during standing on a fixed base (Peterka, 2002).

Yet, these percentages of dependence on sensors are changed depending on environment. For instance, the body will increase relying on vestibular and vision to control balance in an unstable surface and somatosensory input can be even more heavily weighted if the human is in a condition of interrupted vision (Peterka, 2002). Therefore, it can be expected that a sensory input become richer depending on conditions and is weighted more or less by prior knowledge after getting information from conditions (Peterka, 2002).

2.5.1. Somatosensory

The human body can feel pain, cold and touch and the ability to know what is happening in our body is made possible through somatic sensation which sensitively reacts to stimuli (e.g. skin pressure, joints and muscles positions and distension of organs and the temperature of the limbs and brain) detected by receptors (Bear et al., 2001).

A single sensory receptor can encode stimuli features such as intensity, duration, position, and sometimes direction. But a single stimulus usually activates many receptors. The central nervous system interprets the activity of the vast receptor array and uses it to generate coherent perceptions (Bear et al., 2001).

According to Bear et al. (2001) the somatosensory system stands out from other sensory systems for two reasons:

- The receptors of the somatosensory system are evenly spread all over the body instead of being concentrated in specialised areas
- The somatosensory system reacts to a wide range of stimuli that can be considered to include four senses (touch, temperature, pain and position of the body) as a group. Moreover, those four senses can also be broken down into many other senses.

As a result, the somatosensory system includes many sensations (Bear et al., 2001).

According to Bear et al. (2001) the somatic motor control system is made up of the following:

- "The spinal cord command and the control of coordinated muscle contradiction"
- "The brain's command and the control of the motor programs in the spinal cord"

The somatosensory system information is generated to control muscle reflexes received by proprioception (sense of body position) which is information from proprioceptors in muscle spindles and golgi tendon organs (Bear, et al., 2001). The duty of proprioceptors is transducing information about the relative configuration of the body segments (Latash, 2008).

Muscle spindles, which are called also 'stretch receptor', are sophisticated structures deep inside of skeletal muscles (Bear, et al., 2001) and sense the length and velocity of muscle fibers and give information to other neurons within CNS (Latash, 2008). A muscle spindle consists of several muscle fibers, Ia sensory axons (wrapped on muscle fibers) and a fibrous capsule (covers the muscle fibers and Ia axons) (Bear, et al., 2001). Therefore, these receptors provide a sense of the body in space, giving us information on where and how the body is moving and positioned (Bear, et al., 2001).

Another group of proprioceptors in skeletal muscle called 'golgi tendon organs' is located in junction between muscle fibers and tendons (Latash, 2008) and composed

of collagen fibrils and Ib axons (Bear, et al., 2001). Golgi tendon organs sense muscle force while the tendon is deformed by muscle activities, therefore, it is considered a perfect force sensor (Latash, 2008).

2.5.2. Vision

Humans may depend on information from vision if information is received from more than one modality, as the human brain recognises vision information as one of the more reliable references (Latash, 2008). Colour, form, and movement are perceived through vision and different cells of the visual system work to process those (Bear, et al., 2001). The importance of visual information can be seen through experiments standing with eyes closed and eyes open. Standing with eyes closed makes postural stability worse (e.g. an increase in body sway related to larger deviations of COM) (Latash, 2008).

Moreover, visual information allows humans to identify a target and helps locate it in space while correcting its ongoing movements (Latash, 2008). For example, if a pattern on the wall moves away from a standing person, the body sways forward and there will be a backward body sway if the pattern seems to be coming toward the person (Latash, 2008).

2.5.3. Vestibular System

Monitoring the position of the head, coordinating movement of the head and eyes, reading sense of balance and equilibrium, and correcting body posture are carried out by the vestibular system (Bear, et al., 2001).

Among all our senses, the sense of balance is the one we give the least priority and it is usually only when the body loses balance that the individual realises its importance (Latash, 2008). The vestibular system is placed in the inner ear and contains three semi-circular canals and otolith organs (utricle and saccule) which are called the vestibular labyrinth (Bear, et al., 2001). Information on the orientation of

the head relative to gravity is obtained through signals from the vestibular system of the brain and the inner ear (Latash, 2008).

The vestibular system can be classified by the dynamic function (from the semicircular canals) and the static function (from otoliths) (Latash, 2008). The semicircular canals work for the dynamic function and these are especially sensitive to detect rotational movement (angular acceleration) via stimulated cilia of hair cells in the cupular due to the flow of the ampulla, which fills the semicircular canals, when the head rotates (e.g. when the head is shaking from right to left or nodding up and down) (Bear, et al., 2001). Moreover, information from the dynamic function helps the reflex control of eye movements (Latash, 2008). Similar to the semicircular canals, the otolith organs are also mediated by hair cells in the untricle and saccule via movement of head (tilted or accelerated in a certain direction) (Latash, 2008). However, the otolith organs are affected by linear acceleration and head angle (Bear, et al., 2001) as these organs influence the static function (Latash, 2008). The orientation of vestibular maculas (sensory epitheliums in otolith organs) can be different between the untricle and saccule. For instance, the saccule has vertically oriented maculas and the unticle's maculas are horizontally oriented during upright head position (Bear, et al., 2001). Yet, when the head is tilted or moves, the orientations of maculas are slightly changed (polarisation) and which means the cilia of hair cells and gelatinous cap in maculas are pulled because of gravity (Bear, et al., 2001).

2.6. Researching into Dance

2.6.1. The Need of Dance Study

Ballet dancers are required to be expert in controlling movement and balance (Schmit et al., 2005). Considering the artistic aspect, it is difficult to evaluate dance objectively. Performing dance involves various movements such as turns and jumps. Thus, dancers need to understand how to coordinate their whole body stably to perform specific movements from one posture to the next one (Gretchen, 1989). In addition, sports biomechanical analysis will be very helpful to understand how to control the body as well as preventing frequent injuries when dancing.

In particular, Classic Ballet is referred to as the basis of all dances. Numerous dancers and athletes of specific sports categories get training to build basic skills and to then build better skills. Accordingly, research on the ballet movements and techniques will help the advancement of other diverse dance forms, and will be very resourceful in understanding the techniques of the sports categories such as Gymnastics or Figure Skating that require rotation and sense of equilibrium.

2.6.2. Previous Dance Studies Related to Standing Balance

There are a few biomechanics studies into heels off positions of ballet such as Elevé and Relevé. Elevé means ‘rise’ and rising heels up (demi or pointe) without bending joints on legs (plié). Relevé means ‘lifted’ and it is similar to Elevé but the dancer performs this position with plié. However, meanings of these terms have been confused and normally just rising heels is considered as Relevé, which is standing on toes or tip toes.

Albers et al (1992/1993) compared foot plantar pressures through a force plate depending on several conditions such as self-placed walking barefoot, self-placed walking in pointe shoes, elevé en pointe and relevé. Some reliable facts demonstrated that walking barefoot was significantly different to other conditions and the comparison between walking in pointe shoes and relevé position was significant.

A foot analysis from rising to full pointe to lowering was investigated by Dozzi and Winter (1993/1994). During rising phase, it was pointed out that muscles near the metatarsal-phalangeal joints work almost 3 times harder than muscles around the ankle joints and it was recommended to wear pointe shoes when dancers need to perform these.

A relevé test using EMG to find out the effect of fatigue between professional dancers and non-professional dancers was carried out by Yoshida and Kuno-Mizumura (2003). Electrodes were attached over 5 muscles (medial gastrocnemius, lateral gastrocnemius, soleus, and tibialis anterior). The result was similar between the two groups. Yet, a greater range of motion of the ankle, a greater EMG activity from all muscles during the concentric phases and a more resistant soleus were found in the dancer group than the non-dancer group.

Masso et al. (2004) investigated differences in muscle activity and motion for relevé between parallel (6th position) and turn out positions (1st position). An important observation was that plantar flexion angle and the abductor halluces activity in parallel position were higher than in 1st position. However, the muscle activity of medial gastrocnemius was greater in 6th position.

Lin et al. (2005) reported a comparison of relevé en pointé between dominant and non-dominant sides. Dancers managed well to control the ankle on the dominant side, therefore, it was suggested that keeping the dominant side was the fundamental controlling skill in ballet.

Tseng (2010) investigated ballet standing balance in 5 different conditions (parallel position in flat foot, 1st position in flat foot, 1st position in demi pointe, 2nd position in flat foot and 2nd position in *demi pointe*). Participants from non-exercise, recreational runner and ballet dancer groups were attended for this experiment and they performed three 30 sec trials. COP_{left}, COP_{right} and COP_{net} in different ballet poses were collected and standard deviation (SD), approximate entropy (ApEn) and cross-approximate entropy (cross-ApEn) were used to analyse a relation between COP_{left} and COP_{right} trajectories and COP_{net}. There was a significant effect of poses in the

SDs of COP_{left} and COP_{right} and COP_{net} and SDs of ML directions were not significantly different between groups.

As stated above, many ballet standing and posture studies have been studies in various ways of analysis, however, there is not any specific balance investigations in dance area, especially, measuring balance in various types of shoe and there are many ballet movements and positions which can be scientifically researched into ballet balance studies. Therefore, this dance balance research area is worthwhile to develop dance in sports biomechanics.

2.6.3. Dancing on Pointe

Shah (2009) explained about details of a pointe shoe. As illustrated on Figure, the anatomy of the pointe shoe is much more complex than that of flexible ballet shoe. The shoe is tied at the ankle by a satin ribbon; the toes are maintained in a rigid toe box; the top of the box covering the toes called the vamp can be altered in size and length in order to fit perfectly with the dancer's feet (Figure 2.7). Finally, the insole, outer sole and shank (supporting spine for the foot) are in leather. The latter can be reinforced to make a double shank for a better support of the foot, especially for ballerinas with very flexible feet (Shah, 2008).

The most common injury for ballerinas is indeed the foot and ankle injuries such as ankle sprains, hallux valgus, hallux rigidis, flexor hallucis, longus tendonitis, posterior impingement syndrome, lisfranc joint sprains, lisfranc fracture/dislocations and stress fractures (Shah, 2009). Increasing intensity of training on pointe shoes may cause injuries and it is important to perform accurate and efficient techniques on pointe to reduce injuries (Pearson, 2012). The ability for a dancer to successfully dance on pointe depends on their foot type and instep flexibility (Shah, 2009). The ideal condition for a dancer is to be able to perform without pain, injury or body stress (Shah, 2009).

According to Ogilve-Harris et al. (1995) and Spector (2009), a foot with the first three toes of the same length is the best foot type since this configuration allows spreading the weight evenly between the toes. This foot type is called “peasant” or “Giselle”. However, a foot type with the second toe longer than the first will cause calluses, pain and hallux rigidis. This foot type is called “Grecian” or “Morton’s”. Lastly, ‘’Egyptian’’ foot has a long big toe with the lengths of other toes gradually getting shorter.

Having a good shape of the foot is really important to dance ballet even with pointe shoes (Marr, 1983). It is one of the reasons why Russian ballet schools, when choosing dancers, look for enough high-arched and supinated feet when they are around 8 years old because their ability will be better (Shah, 2009). Also, dancers train hard to stretch the feet to have more flexible feet (Marr, 1983).

Shah (2009) explained about foot arch shapes. Depending on the arch of the foot, it can be described by three types of shape: neutral, planus and cavus. The one with the highest arch is called the cavus foot. This shape is beautiful, yet it might cause injuries because of poor shock absorption through the rigid foot arch. The worst type of foot for dancing is the pes planus foot. With this type of foot, it is difficult to dance

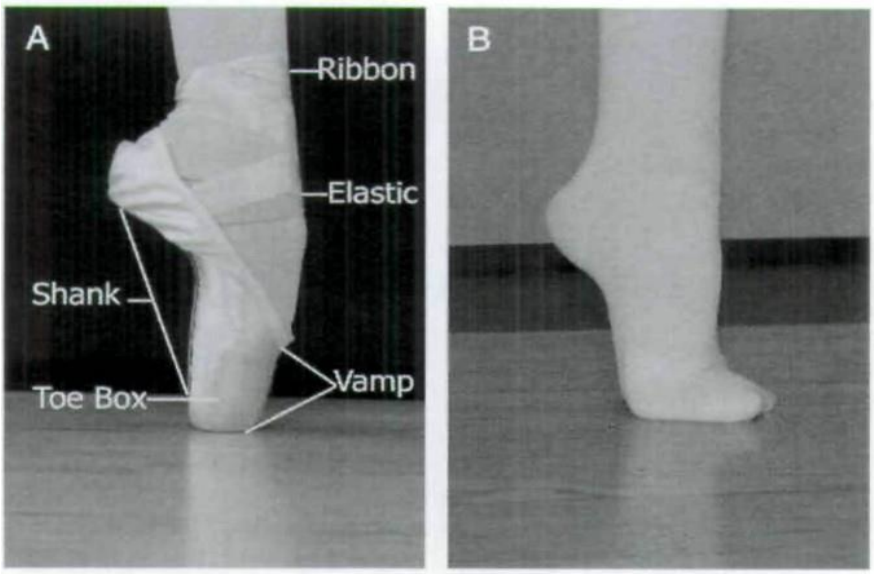


Figure 2.7: A. Pointe shoes balance on tip toes and anatomy of pointe shoe, B. Demi-pointe balance without wearing pointe shoe (Shah, 2009)

on tip-toes due to a lack of plantarflexion ability and the dancer might get injuries easily when ‘over-pointed’ foot (over pronated) happens (Albisetti et al., 2010).

The most ideal position of standing on the toe in both wearing pointe shoes and ballet shoes should have the foot and tibia aligned. Demi-pointe in ballet shoes requires the dancer to perform 70°-90°of dorsiflexion on the metatarsophalangeal (MTP) joints and the ankle and mid foot become platarflexion (ankle plantarflexion) on to the dorsiflexed toes (Bronner et al., 2008). However, there is no dorsiflexion of the toe with pointe shoes toe-standing. The foot is required to perform plantarflextion with a minimum of 90° of the foot and ankle complex to stand on pointe (Shah, 2009; Victor, 2011). Shah (2009) explained that Subtalar joint is fixed between the posterior lip of the tibia and the calcaneus when the full pointe is performed so the ankle can stay stable. Oppositely, the subtalar joint becomes less stable in *demi pointé*, therefore, this fact might be risky to cause ankle inversion injuries (Shah, 2009).

2.6.4. Dance Injuries and Its Prevention

Musculoskeletal injuries may be caused by a repetition of impact loads when walking or running (Nigg et al., 1995). Athletes’ injuries can be caused by overloading while the athletes’ legs are misaligned relative to the ground (Nigg, 1985). Seventy eight percent of the anterior cruciate ligament injuries, that happen while being engaged in sports activities, are of the non-contact injury type that occurs when changing directions or when landing on the ground after jumping and these are not caused by contact with other party during a game (Noyes et al., 1983). Injury may result due to the drastic deceleration prior to changing direction, wrong landing after jumping up, and failure to adjust the direction (Noyes et al., 1983; Griffin et al., 2000).

Dance includes diverse jumps and movements for landing that can cause severe impacts force. For example, training program for ballet performance includes the movement that entails landing after demonstrating jumping, approximately 200 times, and dancers need to perform this movement every day (Liederbach et al., 2006). This movement can exert significant impacts on the knees, which increases the risk

of injury. Dancers' anterior cruciate ligament injury rate is 0.009 injuries out of 1000 cases, which is lower than the anterior cruciate ligament injury rate of the professional athletes who specialise in games that require use of a ball (Liederbach et al, 2008). This is because dancers can land softly since they are trained on the landing from a young age (Liederbach et al., 2008; Orichimo et al., 2009). In addition, 56% of dancers have experienced injuries and the most common ones were ankle injuries (49%) and knee injuries (16%) (Wiesler et al., 1996). Injury to the lower body occurs due to the inaccurate 'Turnout' but also due to imbalance of the soft tissue and distortion resulting from decreased activities of the musculus quadriceps femoris because of frequent plie and pointé resulting in fatigue (Kwon, 2001).

Therefore, dance balance studies will apply for reducing injuries and not only developing or defining the movement and it is expected that some reasons why dancers are often injured in specific positions or movements will be found through researching into dance balance from static to dynamic posture control studies.

CHAPTER 3

METHODS

3.1. Subjects

All subjects who volunteered for the studies were members of the Loughborough University dance club or the Loughborough gymnastics club and the subjects had been training dance or gymnastics for more than 8 years. Informed consent forms and subject information sheets which complied with the Loughborough University Ethical Advisory Committee (Appendix 1 & 2 depending on which study the subjects were involved in) were read and agreed by all subjects. None of the subjects had been injured or had been in pain in the last year before taking part in the studies.

3.1.1. The 1st Study (static balance): A balance study into ballet 2nd position between 2 types of shoes (ballet shoes and pointe shoes)

Eight female dancers were recruited from the Loughborough University dance club and their ages ranged from 19 to 26 years old. All ballet dancers had danced ballet for a long period (more than 10 years) since childhood and were training in the advanced group. All dancers were trained dancing on pointe (standing on the tip toes in ballet).

3.1.2. The 2nd study: Balance control and response to perturbations whilst standing on double leg stance dance positions using a moving platform

Eight healthy female dancers aged 22.9 ± 2.2 years, height 1.65 ± 0.06m and mass 59.1 ± 9.1 kg (mean ± SD) from Loughborough Student Union Dance Club volunteered for the study. None of them had any health issues, injuries or were pregnant. The dance club runs from recreation levelled dancers to advanced dancers but all subjects had been dancing for more than 10 years. They were all performing ballet, jazz and contemporary dances and the subjects were in at least

one of the highest level classes in either ballet, jazz or contemporary dance in the dance club.

3.1.3. The 3rd study: Comparisons of balance control and response to perturbations in one leg standing dance positions between dancers and gymnasts

Sixteen subjects (eight subjects in each group, dancers vs gymnasts) aged 20.44 ± 1.9 years, height 167.04 ± 8.44m and mass 61.47 ± 8.59. Gymnasts and dancers were from the 1st team of their sport teams in the university and experienced in their performances for more than eight years, and had competed in many competitions. More information on the subjects in each group is shown in Table 3.1.

Table 3.1: Means of subjects information in groups depending on genders

	Dancer Group		Gymnast Group		Total
Gender ratio	Females	Males	Females	Males	16
	7	1	6	2	
Age	Females	Males	Females	Males	20.44
	20	20	21.67	18.5	
	Total		Total		
	20		20.88		
Height	Females	Males	Females	Males	167.04
	168.27	178	160.83	175.85	
	Total		Total		
	169.49		164.59		
Mass	Females	Males	Females	Males	61.47
	63.78	75.43	55.13	65.45	
	Total		Total		
	65.24		57.71		

3.2. Data Collection

The Vicon optoelectronic motion capture system (Vicon, Oxford Metrics Group) including two Bertec strain gauge force plates was used for all three studies. The Electromyography (EMG) system (Trigno wireless EMG, Delsys) and a Stewart platform were additionally included to the whole system to collect data for 2nd and 3rd studies. The Force plates were embedded into the platform to perturb balance to ascertain the reaction after stimuli (Platform movements).

All those systems were integrated into and controlled by the Computer Assisted Rehabilitation Environment (CAREN) system (CAREN virtual reality environment, Motek Medical). All data from each system was synchronised via the Vicon MX Giganet control box after force and EMG data was being converted to digital data through the Analog-to-Digital Converter (ADC) in the MX Giganet box (Figure 3.1).

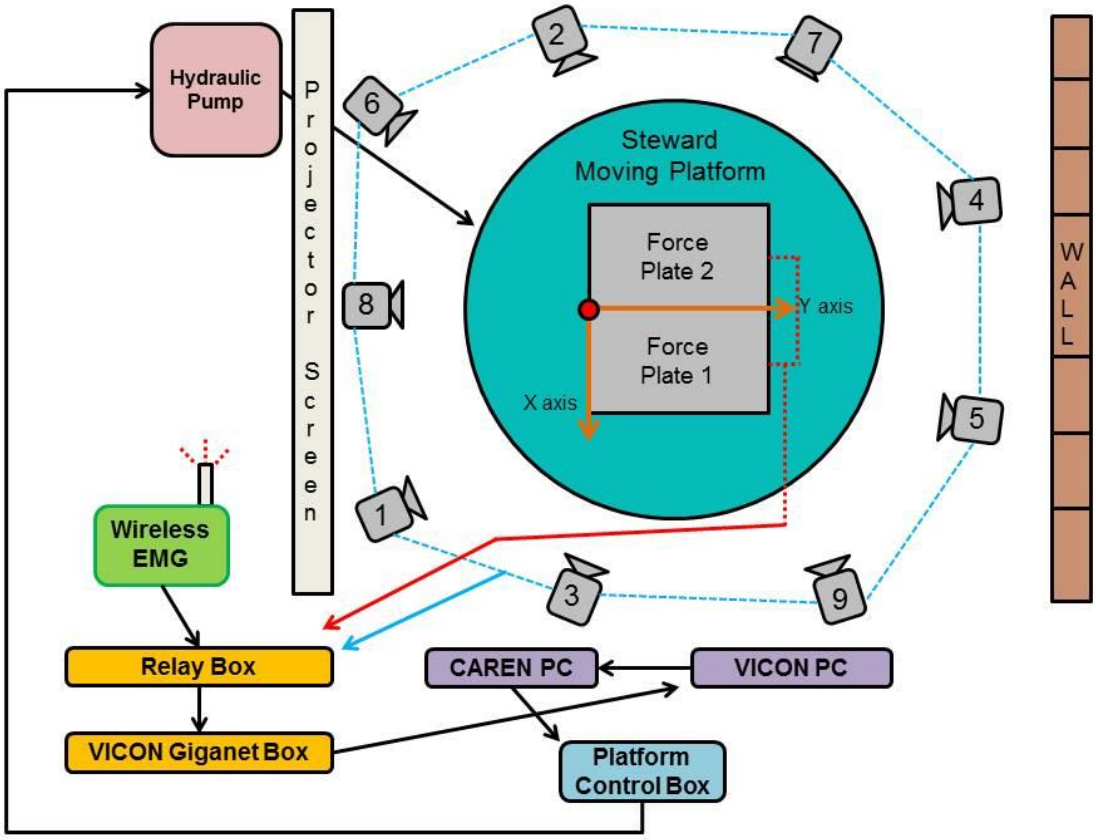


Figure 3.1: The CAREN system including all other equipment for the studies

For the data collections for all studies, kinetics data (from one or two force plates depending on the numbers of standing leg) and kinematics data (markers data from Vicon motion capture system) were sampled at the frequency of 2000 Hz and 200 Hz respectively. The sample rate of EMG was the same as the force data rate (2000 Hz) for the 2nd and 3rd studies.

3.2.1. Kinematics Data

During all data collections for the three studies, nine T20 Vicon cameras were used to collect kinematic data (Figure 3.2). T20 Vicon cameras have the maximum frame rate at 690 frames per second (690 Hz) with full resolution of 2 megapixels (1600 ×1280). The frame rate for all 3 studies was chosen to collect kinematic data at 200 frames per second (200 Hz).

Figure 3.2: Vicon T series camera

Each Vicon camera takes 2 dimensions (2D) images then the combined images from more than one camera create 3 dimensions (3D) coordinate system. Therefore, the optoelectronic Vicon motion capture system can detect each reflective marker in the 3D coordinate system. For the calibration, Vicon's dynamic calibration frame (with five 14 mm markers on a T shaped metal wand frame) was waved quickly to create a calibrated cube from the surface of the platform to about 3 m in height, 3 m in width and 3 m in depth which could cover all the movements of the subjects including their whole body (Figure 3.3). Then, the T shaped frame was placed on the middle and left sides of the pair of force plates to create the origin of the global coordinate system (GCS). All nine Vicon cameras were installed to be able to observe the Stewart platform, including subjects' movements, by surrounding the platform from above. Six cameras were fixed on metal frames (4 cameras between 3.31 m and 3.35 m height from the origin level/ No.1 and No.6 were placed at 2.45 m and 2.48 respectively) and another two cameras (No.4 & No.5) were placed on the right side of the laboratory wall at a

height of 1.4 m and 2.2 m respectively. Residual error in pixels from all cameras was below 0.252 and the mean residual for all cameras was 0.186 in pixels. The whole CAREN system in the laboratory including the nine cameras' placement is shown in Figure 3.1.

Figure 3.3: Vicon dynamic calibration frame

Forty seven reflective markers (14 mm) were attached on each dancer for the 1st study and 53 reflective markers (including 4 on the platform and 2 on both heels) were used for the 2nd and 3rd studies. For these last two studies, 34 markers of 14 mm diameter and 21 bigger markers (the diameter of 25 mm: C7, T10, L1, sternum, xiphoid, 4 markers on the elbows, 4 markers on the wrists, 4 markers the knees, 4 markers the ankles) were used (Figure 3.4).

Figure 3.4: Reflective markers used for studies (14 mm & 25 mm)

These markers divided the body into 17 segments and the total number of segments was 18 segments, including the force plates. All the marker placement information is shown in Table 3.2.

Table 3.2: Marker placement and created segments to collect kinematic data

Segments		Marker Label		Marker Position	Description and Directions
1	Head	1	Head_F_Right	Four markers placed at front right/left and back right left of the head	
		2	Head_F_Left		
		3	Head_B_Right		
		4	Head_B_Left		
2	Trunk (including R&L_Acromion)	5	Sternum	Superior tip of the manubrium of the sternum	Suprasternal notch at top of sternum
		6	Xiphoid	Centre of the xiphoid process of the sternum	Inferior tip of sternum
		7	C7	The 7th cervical vertebra	Prominence at base of neck when the neck is flexed
		8	T10	The 10th thoracic vertebra	Count up 3 from L1 (moving the skin over the spinous processes)
		9	L1	1st Lumbar vertebra	Find L5 between right and left PSIS and count up 4
		10	R_Scapula	Middle of right scapula	Used only for identification of right side
3	Right_Upper_Arm	11	Right_Anterior_Shoulder	Estimated anterior projection of the right glenohumeral joint centre when in the anatomical position	Mid-pointe of these two markers is the sight shoulder joint centre
		12	Right_Posterior_Shoulder	Estimated posterior projection of the right glenohumeral joint centre when in the anatomical position	
		13	Right_Acromion	Superior tip of the right acromion process	
		14	Right_LE	Frontal plain of right lateral humeral epicondyle	Medial and lateral projections of the right elbow joint centre) mid-point of these two markers is the right elbow joint centre) / elbow extended
		15	Right_ME	Frontal plain of right medial humeral epicondyle	
4	Right_Lower_Arm (including Right_LE & ME)	16	Right_LW	Frontal plain of the styloid process of the right radius (lateral)	Medial and lateral projections of the right wrist joint centre (mid-point of these two markers in the wrist joint centre)
		17	Right_MW	Frontal plain of the styloid process of the right ulna (medial)	
5	Right_Hand (including Right_LW & MW)	18	Right_3MP	Doral aspect of the head of the right 3rd metacarpal	
6	Left_Upper_Arm	19	Left_Anterior_Shoulder	Estimated anterior projection of the left glenohumeral joint centre when in the anatomical position	Mid-pointe of these two markers is the left shoulder joint centre
		20	Left_Posterior_Shoulder	Estimated posterior projection of the left glenohumeral joint centre when in the anatomical position	
		21	Lef _Acromion	Superior tip of the left acromion process	
		22	Lef _LE	Frontal plain of the left lateral humeral epicondyle	Medial and lateral projections of the left elbow joint centre)mid-point of these two markers is the left elbow joint centre) / elbow extended
		23	Left_ME	Frontal plain of the left medial humeral epicondyle	
7	Left_Lower_Arm (including Left_LE & ME)	24	Left_LW	Frontal plain of the left styloid process of the right radius (lateral)	Medial and lateral projections of the left wrist joint centre (mid-point of these two markers in the left wrist joint centre)
		25	Left_MW	Frontal plain of the left styloid process of the right ulna (medial)	

8	**Left_Hand (including Left_LW & MW)**	**26**	**Left _3MP**	Doral aspect of the head of the left 3rd metacarpal	
9	**Pelvis**	**27**	**Right_ASIS**	Anterior superior iliac spine, in line with hip joint centre	Bony landmark on the front of the pelvis (level with the belt)
		28	**Left_ASIS**		
		29	**Right_PSIS**	Posterior superior iliac spine	Dimple in the skin at the back of the pelvis (a little lower than ASIS)
		30	**Left_PSIS**		
		31	**Right_Hip**	Greater trochanter of the femur	Palpate the upper and lower aspects, and place in centre
		32	**Left_Hip**		
		33	**L_Hip**	Superior border of left iliac crest	Used only for identification of left side
10	**Right_Thigh (including Right_Hip)**	**34**	**Right_LK**	Fontal plane of the right lateral femoral epicondyle	Medial and lateral projections of the right knees joint centre (mid-point of these to markers is the right knee joint centre) - knee extended
		35	**Right_MK**	Fontal plane of the right medial femoral epicondyle	
11	**Right_Shank (including Right_LK & MK)**	**36**	**Right_LA**	Fontal plane of the right lateral malleolus of the fibula	Medial and lateral projections of the right ankle joint centre (mid-point of these two markers in the right ankle joint centre)
		37	**Right_MA**	Inferior tip of the right medial malleolus of the tibia	
12	**Right_Foot (including Right_LA & MA)**	**38**	**Right_Heel**	Middle of right calcaneus	Used for the 2nd and 3rd studies (not the 1st study)
		39	**Right_1MPT**	Side of the right 1st metatarsal (the 2nd and 3rd studies/ on the head for the 1st study)	Medial and lateral projections of the right MTP joint centre (mid-point of these two markers in the right MTP joint centre) - knee extended
		40	**Right_5MPT**	Side of the right 5th metatarsal (the 2nd and 3rd studies/ on the head for the 1st study)	
13	**Right_Toe (including Right_1MPT & 5MPT)**	**41**	**Right_Toe**	End of the right 1st distal phalanx	Tip of the right big toe
14	**Left_Thigh (including Left_Hip)**	**42**	**Left_LK**	Fontal plane of the left lateral femoral epicondyle	Medial and lateral projections of the left knees joint centre (mid-point of these to markers is the left knee joint centre) - knee extended
		43	**Left_MK**	Fontal plane of the left medial femoral epicondyle	
15	**Left_Shank (including Left_LK & MK)**	**44**	**Left_LA**	Fontal plane of the left lateral malleolus of the fibula	Medial and lateral projections of the left ankle joint centre (mid-point of these two markers in the left ankle joint centre) -
		45	**Left_MA**	Inferior tip of the left medial malleolus of the tibia	
		46	**Left_Heel**	Middle of left calcaneus	Used for the 2nd and 3rd studies (not the 1st study)
16	**Left_Foot (including Left_LA & MA)**	**47**	**Left_1MPT**	Side of the left 1st metatarsal (the 2nd and 3rd studies/ on the head for the 1st study)	Medial and lateral projections of the left MTP joint centre (mid-point of these two markers in the left MTP joint centre)
		48	**Left_5MPT**	Side of the left 5th metatarsal (the 2nd and 3rd studies/ on the head for the 1st study)	
17	**Left_Toe (including Left_1MPT & 5MPT)**	**49**	**Left _Toe**	End of the 1st distal phalanx	Tip of the left big toe
18 Markers on the force plates (the 2nd and 3rd studies)					
18	**Force plates**	**50**	**Screen_Right**	Right top corner of the 2nd force plate/ Screen side	Used to calculate the origin axes to read platform movements
		51	**Screen_Left**	Left top corner of the 1st force plate/ Screen side	
		52	**Wall_Right**	Right bottom corner of the 2nd force	

				plate/ Wall side	
		53	**Wall_Left**	Left bottom corner of the 1st force plate/ Wall side	

3.2.2. Kinetics (Force) Data

Force data was collected at 2000 Hz via the embedded two Bertec force plates (FP4060-07 strain gauge force plates) into the Stewart platform (moving platform). Each force plate measures the resultant ground reaction forces and horizontal (X: medial-lateral, Y: forward-backward) and vertical (Z) moments (in total six components) as well as the COP X and Y (Bertec, 2015). This force plate model uses a 16-bit digital gain amplifier and signal conditioning unit to calculate the six components in digital units before the signal being synchronised in the MX Vicon Giganet control box then data is converted back to analogue signal (Bertec, 2015). The size of each force plate is 600 mm (length) by 400mm (width) therefore the size including both force plates is 600mm × 800 mm.

The COP is calculated using moments, forces and the origin of each force plate [O_x,O_y,O_z] (Figure 3.6). The COP can be measured via:

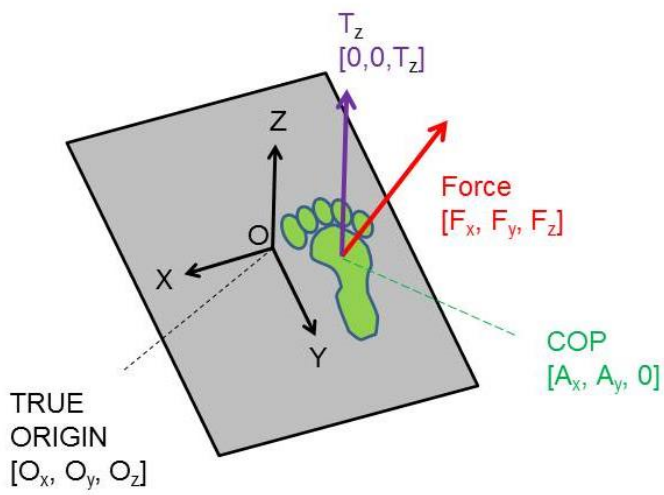


Figure 3.6: Coordinates of true origin, Force, COP and free vertical torque

$$\mathrm{M} = \mathrm{F} \times \mathrm{D} \tag{5}$$

$$\mathrm{M} = \left[F_x, F_y, F_z\right] \times \left[A_x - O_x, A_y - O_y, -O_z\right] + [0, 0, T_z] \tag{6}$$

$$\begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} 0 & O_z & A_y - O_y \\ -O_z & 0 & -(A_x - O_x) \\ -(Ay - Oy) & Ax - Ox & 0 \end{bmatrix} \times \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ T_z \end{bmatrix}$$

$$= \begin{bmatrix} \left(A_y - O_y\right)F_z + O_z F_y \\ -O_z F_x - (A_x - O_x)F_z \\ (A_x - O_x)F_z - \left(A_y - O_y\right)F_x + T_z \end{bmatrix} \tag{7}$$

$$A_x = -\frac{M_y + O_z F_x}{F_z} + O_x \tag{8}$$

$$A_y = -\frac{M_x - O_z F_y}{F_z} + O_y \tag{9}$$

$$T_z = M_z - (A_x - O_x)F_y + (A_y - O_y)F_x \tag{10}$$

Where:

M = Moment

F = Force

D = Distance

Mx = Moments about X axis

My = Moments about Y axis

Mz = Moments about Z axis

F_x *= Medio-lateral force*

F_y *= Anterior-posterior force*

F_z *= Vertical force*

O_x *= X-Coordinate of true origin*

O_y *= Y-Coordinate of true origin*

O_z *= Z-Coordinate of true origin*

A_x = *X-Coordinate of force application point (COP, Centre Of Pressure)*

A_y = *Y-Coordinate of force application point (COP, Centre Of Pressure)*

T_z = *Free moment, free vertical torque, frictional torque*

3.2.3. EMG Data

The Delsys Trigno™ wireless system (Delsys Inc., Boston) was used for the 2nd and 3rd studies to determine EMG latencies after the platform movement. The EMG system has 16 wireless surface sensors. Externally, each sensor has 4 electrodes on the bottom surface, which are placed on the skin, one LED light which gives indicator status on the top, one button for the sensor's power and pairing on the top of the sensor and 4 small metal components on both sides (two each) to charge a built-in battery from the EMG base station. The 4 electrodes are placed in parallel on both sides and these electrodes read signals from muscles between two electrodes (top and bottom) then combine from both sides. In total, the EMG system has 64 channels of information (EMG - 16 channels, and triaxial accelerometer X, Y, Z from each sensor, - 48 channels). The EMG system has the transmission range of 40 m, 16-bit signal resolution and sampling rate up to 4000 samples per second (Delsys Inc., 2009). Analogue EMG signal was taken from the Trigno base station into the relay box with time delay of 48 ms before being synchronised with other data. Therefore, this time delay was subtracted from EMG latencies.

If it was necessary, hair was shaved using a disposable razor from the skin to reduce noise before the EMG sensors were placed. Also all the areas of EMG attachment were cleaned using an alcohol wipe to remove dead skin cells. The EMG sensors were attached on the skin of muscle bellies while being parallel to muscle fibres with Delsys double sided adhesive tape with custom holes cut out for the electrodes.

16 EMG and 11 EMG sensors were used for the 2nd study (both legs standing balance) and 3rd study (one leg standing balance) respectively (Table 3.3 & Table 3.4) and the sampling rate was 2000 Hz for both studies.

Seven trials of Maximum Voluntary Contraction (MVC) were taken from the muscles, where each EMG sensor was attached on, before starting experiments.

Table 3.3: Attachments of EMG sensors for the 2nd study

EMG Label No.	Sensor Positions (on the bellies of muscles below)	Description and Directions
1	Right Rectus Abdominis (above navel level) (trunk flexion, hip flexion)	- Place on the middle of muscles segments (both right and left) above umbilicus level but few centimetres from vertical umbilicus line
2	Left Rectus Abdominis (above navel level) (trunk flexion, hip flexion)	
3	Right Lumber Paraspinal (trunk flexion, hip flexion)	- With standing normal, find L3 level on both sides from L1 marker
4	Left Right Lumber Paraspinal (trunk flexion, hip flexion)	
5	Right Glutus Medius (right hip abduction & medial rotation of hip)	- Placed on lateral aspect of hip and above the greater trochanter - With rising the leg to the side (abduction), about 5-7 cm back lined with ASIS - If it is hard to find, repetition of abduction and adduction may help
6	Left Glutus Medius (right hip abduction & medial rotation of hip)	
7	Right Rectus Femoris (knee extension & hip flexion)	- In sitting with the knee fully extended parallel to the ground, find a place between anterior inferior iliac spine and patella on anterior surface of thigh - Find the distal end of the rectus femoris muscles (where the muscles start to be seen) and find a place about 5-10 cm proximal to this point
8	Left Rectus Femoris (knee extension & hip flexion)	
9	Right Long Head of Biceps (knee flexion & hip extension)	- With standing, on the middle of lateral posterior surface of thigh - Look for a place 10-15 cm proximal to the distal aspect of the biceps femoris muscles
10	Left Long Head of Biceps (knee flexion & hip extension)	
11	Right Tibialis Anterior (ankle flexion, mainly dorsiflexion & inversion)	- In sitting with the ankle dorsiflexion, find tibialis anterior on the anterolateral shank - look for a place slightly up from the middle of shank in length
12	Left Tibialis Anterior (ankle flexion, mainly dorsiflexion & inversion)	
13	Right Peroneus Longus	- In sitting with the ankle eversion, push the

	(ankle eversion, assist plantar flexion)	outside of foot against the eversion - On the lateral shank, look for a place between the knee joint centre and deep-set line
14	Left Peroneus Longus (ankle eversion, assist plantar flexion)	
15	Right Gastrocnemius (ankle extension, mainly plantar flexion & assists flexion of knee)	- With standing on toe, look for the belly of medial gastrocnemius
16	Left Gastrocnemius (ankle extension, mainly plantar flexion & assists flexion of knee)	

Table 3.4: Attachments of EMG sensors for the 3rd study

EMG Label No.	Sensor Positions (on the bellies of muscles below)	Description and Directions
1	Tibialis Anterior (ankle flexion, mainly dorsiflexion & inversion)	- In sitting with the ankle dorsiflexion, find tibialis anterior on the anterolateral shank - look for a place slightly up from the middle of shank in length
2	Peroneus Longus (ankle eversion, assist plantar flexion)	- In sitting with the ankle eversion, push the outside of foot against the eversion - On the lateral shank, look for a place between the knee joint centre and deep-set line
3	Gastrocnemius (ankle extension, mainly plantar flexion & assists flexion of knee)	- With standing on toe, look for the belly of medial gastrocnemius
4	Rectus Femoris (knee extension & hip flexion)	- In sitting with the knee fully extended parallel to the ground, find a place between anterior inferior iliac spine and patella on anterior surface of thigh - Find the distal end of the rectus femoris muscles (where the muscles start to be seen) and fine a place about 5-10 cm proximal to this point
5	Long Head of Biceps (knee flexion & hip extension)	- With standing, on the middle of lateral posterior surface of thigh - Look for a place 10-15 cm proximal to the distal aspect of the biceps femoris muscles
6	Right Glutus Medius	- Placed on lateral aspect of hip and above

	(right hip abduction & medial rotation of hip)	the greater trochanter
7	Left Glutus Medius (left hip abduction & medial rotation of hip)	- With rising the leg to the side (abduction), about 5-7 cm back lined with ASIS - If it is hard to find, repetition of abduction and adduction may help
8	Right Rectus Abdominis (trunk flexion, hip flexion)	- Place on the middle of muscles segments (both right and left) above umbilicus level but few centimetres from vertical umbilicus line
9	Left Rectus Abdominis (trunk extension, hip extension)	
10	Right Lumber Paraspinal (trunk flexion, hip flexion)	- With standing normal, find L3 level on both sides from L1 marker
11	Left Right Lumber Paraspinal (trunk extension, hip extension,)	

3.2.4. Platform Movements

Platform movements of the Stewart platform were controlled via Motex D-flow software (Motek Medical, Amsterdam) and all equipment was included in the Motek Medical CAREN (Computer Assisted Rehabilitation Environment) system which operates with the accuracy and speed of the real-time predictive feedback loop of a human. The Stewart platform is designed to translate the movement of the platform in six degrees of freedom and the Motek medical D-Flow software controls amplitudes and velocities of the moving platform. The maximum amplitude and velocity of the platform movements are up to 0.15 m and 1.5 $m.s^{-1}$ respectively in horizontal translations. Also this system allows rotations of the platform but only horizontal translations were generated for the studies.

The Stewart moving platform was used to perturb various conditions of balance during the 2nd and 3rd studies while the subject was balancing on it. The platform was moved in two or four directions with two different speeds (slow and fast, varied depending on conditions). More details of platform translations in the studies are explained in 3.3. Procedure.

3.2.5. Anthropometrics

A simplified version from Yeadon's (1990)'s inertia model was applied for the 2nd and 3rd studies. Forty anthropometric measurements, including 10 lengths, 30 perimeters and 5 widths, height and weight were taken from all subjects to get segmental inertia parameters (the original version has 95 anthropometric measurements, Figure 3.7). These measurements divide the body of a subject into 40 solid segments and it calculated mass, distance of mass centre from proximal joint, segment length, principal moment of inertia in triplexes of each segment. For the studies, 14 segments were recreated from the 40 solid segments and each foot was divided in two segments (fore foot: toe & rear foot) for balance conditions standing on demi-pointe in the 2nd study (Table 3.5).

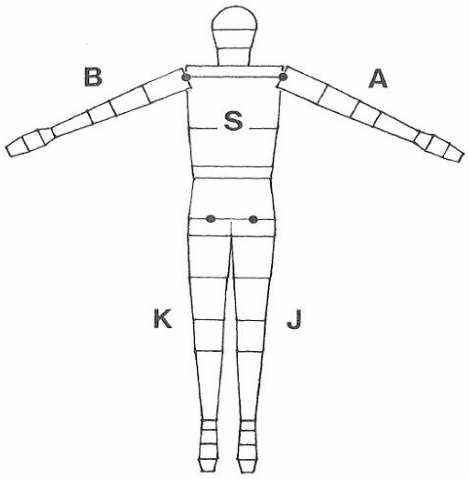


Figure 3.7: Yeadon (1990)'s inertia model which has 40 solid segments in a body

Table 3.5: The changes of body segments in three different versions - 11 original segments, Yeadon (1990)'s 40 solid segments and re-calculated segments (reduced numbers of segments) for the 2nd and 3rd studies

Original Segments	Solid Segments	Re-calculated Segments (for the studies)		
Chest-head	s4, s5, s6, s7, s8	Head & Neck		
Thorax	s3	Trunk		
Pelvis	s1, s2			
Right upper arm	b1, b2	Right upper arm		
Right lower arm - hand	b3, b4	Right lower arm		
	b5, b6, b7	Right hand		
Left upper arm	a1, a2	Left upper arm		
Left lower arm - hand	a3, a4	Left lower arm		
	a5, a6, a7	Left hand		
Right thigh	k1, k2, k3	Right Thigh		
Right shank - foot	k4, k5	Right Shank		
	k6, k7	Right Foot	or	Right rear foot
	k8, k9			Right fore foot
Left thigh	j1, j2, j3	Left Thigh		
Left shank - foot	j4, j5	Left Shank		
	j6, j7	Left Foot	or	Left rear foot
	j8, j9			Left fore foot

3.3. Procedures

To collect data for the studies, a time slot of two hours was booked for each subject and all experimental systems were turned on at least 45 min before the subject came to warm up and reach stable baselines. All subjects were asked to wear tight black shorts and female subjects wore a sports bra and male subjects stayed topless. The subjects performed a self-paced and personalised warm up before starting the balance experiments.

Anthropometric measurements were taken from the subjects on a mat before or after the experiment. For the 1st study, reflective markers were placed on the subjects first as EMG system was not required. EMG sensors were attached on the muscle bellies of the subjects for the 2nd and 3rd studies before reflective markers were

attached to the joints of the subjects. After all reflective markers were attached, two static trials were collected while each subject stood on the Stewart platform. In the anatomical position, subjects positioned their arms with hands upward in the air, then downward with the palms looking forward (anatomical position) to use data to run the auto-labelling function and reconstruct missing markers in Vicon Nexus 1.7.1. The dancers were allowed breaks between the balance positions and they had short breaks anytime they wished depending on their fatigue state.

3.3.1. The 1st Study: A balance study into ballet 2nd position between 2 types of shoe (ballet shoes and pointe shoes)

All eight ballet dancers were asked to perform six trials of five different conditions in ballet 2nd position. These were: flat feet with ballet shoes, demi-pointe (half-toe standing and heels up) with ballet shoes, flat foot with pointe shoes and demi-pointe with pointe shoes and toe-standing (on tip toes) with pointe shoes (Figure 3.8). Each balance trial required the dancers to keep balance for 30 sec on the force plates by.

In total, 30 trials were performed by each dancer and the orders of the balance conditions were randomised to avoid having order effects (Table 3.6). The ballet dancers kept their feet positions in turnout from their hip joints and arms 'A la Seconde' position (stretched arms to the sides with palms forward & elbows backward and normally used with the ballet 2nd feet position) as ballet 2nd position requires.

Table 3.6: Numbers of trials depending on dance positions and shoes performed by each subject

	Ballet Shoes	Pointe Shoes	Trials depending on feet positions
Flat	6 trials	6 trials	12 trials
Demi-pointe	6 trials	6 trials	12 trials
Toe-standing	NONE	6 trials	6 trials
	6 trials X 5 = 30 trials		

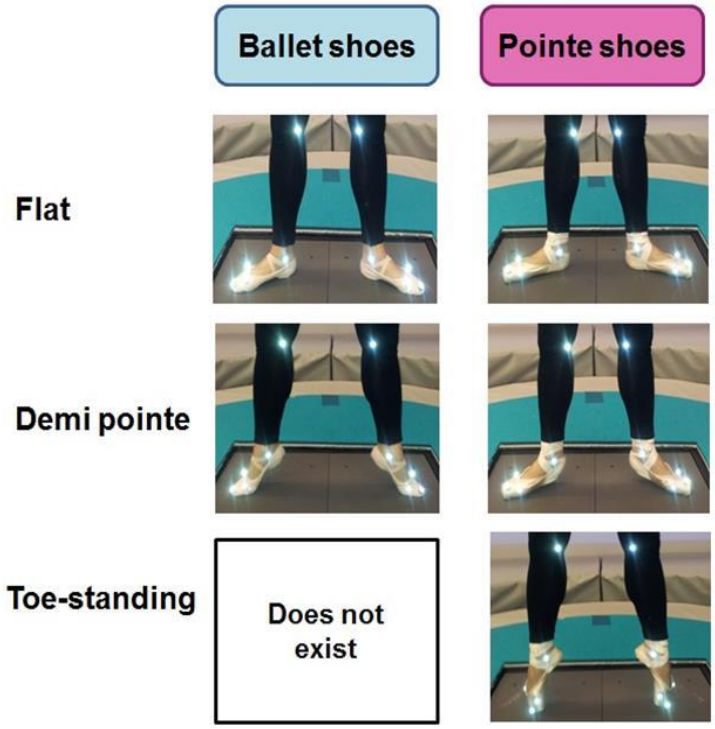


Figure 3.8: Five conditions of ballet 2nd position with ballet and pointe shoes

3.3.2. The 2nd Study: Balance control and response to perturbations whilst standing on double leg stance dance positions using a moving platform

Eight dancers participated in the 2nd study and 16 EMG sensors and 53 reflective markers were attached on the body of dancers. The dancers performed 64 perturbed stance trials in two directions (anterior, posterior) for four dance positions (ballet 2nd position flat feet, ballet 2nd position on demi-pointe feet, contemporary position on flat feet and contemporary position on demi-pointe) on the two force plates (Figure 3.9).

Each dance position contained 16 trials and there were four slow (10 cm at 10 $cm.s^{-1}$ for flat feet positions, 5 cm at 5 $cm.s^{-1}$ for demi-pointe positions) and four fast (10 cm at 20 $cm.s^{-1}$ for flat feet positions, 10 cm at 10 $cm.s^{-1}$ for demi-pointe positions) platform transitions in each direction.

During the experiment, the subjects were not allowed to know the direction or amplitude of the platform movement as these were randomised. Moreover, the order of dance positions was given individually to avoid having order effects (Table 3.7).

Table 3.7: The description of dance positions and external perturbations regarding trials performed by the subjects

Feet Positions	Dance Positions	Speeds	Amplitudes & Velocities	Directions of Platform	Numbers of trial
Standing on **Flat** Feet	♦Ballet 2nd position (Turnout Feet)	Slow	10 cm at 10 $cm.s^{-1}$	Anterior (Forward)	4 times in each direction (4 × 2 = 8 trials)
				Posterior (Backward)	
	♦Contemporary standing position (=normal standing)	Fast	10 cm at 20 $cm.s^{-1}$	Anterior (Forward)	4 times in each direction (4 × 2 = 8 trials)
				Posterior (Backward)	
Standing on **Toes** (Demi-pointe)	♦Ballet 2nd position (Turnout Feet)	Slow	5 cm at 5 $cm.s^{-1}$	Anterior (Forward)	4 times in each direction (4 × 2 = 8 trials)
				Posterior (Backward)	
	♦Contemporary standing position (=normal standing but on toes)	Fast	10 cm at 10 $cm.s^{-1}$	Anterior (Forward)	4 times in each direction (4 × 2 = 8 trials)
				Posterior (Backward)	
Total numbers of trial = 4 (Feet & Dance positions) × 2 (Speeds) × 8 (Directions of platform & Numbers of trial) **= 64 trials**					

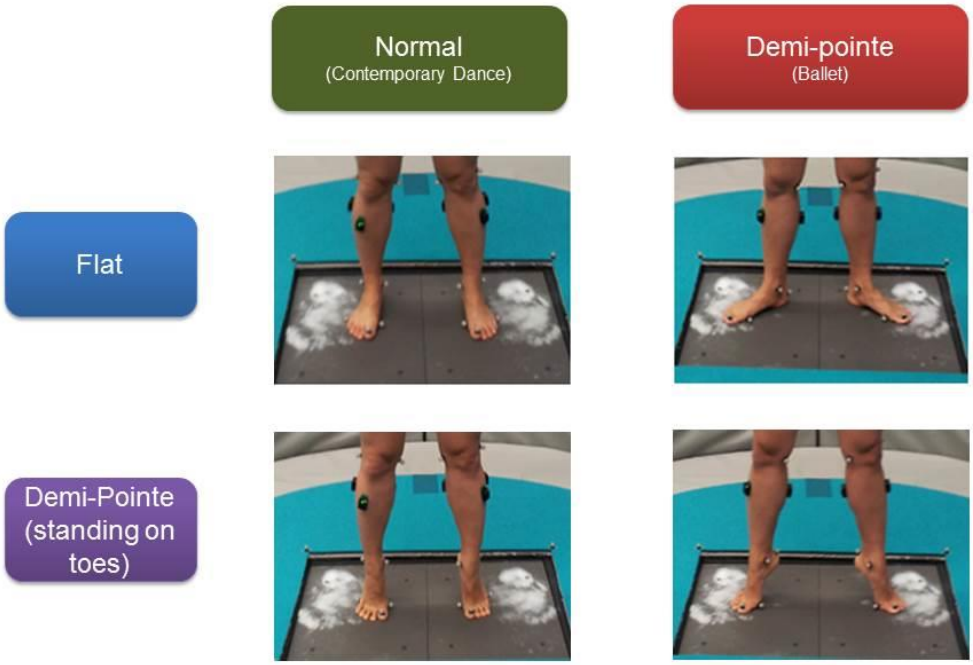


Figure 3.9: Ballet 2nd position (standing on both feet & turnout) and Contemporary dance position (standing on both feet & parallel feet, standing with normal feet position) in Flat and Demi-pointe feet conditions

3.3.3. The 3rd Study: Comparisons of balance control and response to perturbations in single leg standing dance positions between dancers and gymnasts

11 EMG sensors and 52 reflective markers were attached to the 16 subjects' bodies (eight dancers & eight gymnasts). For the balance tests, the subjects chose one leg they preferred to stand on. The subjects performed static flat positions (normal foot position & turn-out position) and static standing on toes positions (demi-pointe position: normal foot position and turn-out position) six times and a maximum of 30 seconds for each position (in total 24 trials) on a force plate. Also, in total 48 perturbed stance trials were collected in anterior, posterior, right and left directions for two dance positions (flat normal & turn-out positions) on the Stewart platform (Figure 3.10).

Each direction of platform movement had three slow and three fast trials (6 trials for each direction). The amplitudes and velocities of the platform movement were configured so that 5 cm amplitude at 5 cm. s^{-1} velocity was the slow perturbation and 10 cm at 10 cm. s^{-1} was the fast platform perturbation. The order of test conditions in the study was randomised to avoid order effects.

Table 3.8: The description of balance test sessions, positions and external perturbations regarding trials performed by each subject (N: Normal, T: Turnout, S: Slow 5 cm at 5 cm.s^{-1}, F: Fast 10 cm amplitude at 10 cm.s^{-1})

Types of balance test environment																				
	Static (max 30 sec each)				**Perturbed (on a moving platform)**															
Up/ Down	Flat		Demi-pointe		Normal								Turnout							**Foot position**
Foot position	N	T	N	T	A		P		R		L		A		P		R		L	**Directions**
Trials	6	6	6	6	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	**Speeds**
					3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**Trials**
	12		12		24								24							
Total	24 trials				48 trials															**Total**

3.4. Data Processing and Analyses

Kinematic and kinetic data from each trial used for the studies were labelled and processed on Nexus 1.7.1 and processed data were saved onto the same named excel file. Data in excel files were then further processed and analysed via MATLAB R2012b.

3.4.1. Joint Centres

Centres of joints were reconstructed via the Bodybuilder 'Body Language modelling' function. The joint centre was calculated from two markers attached on both sides of the joint during experiments.

$$\begin{bmatrix} C_x \\ C_y \\ C_z \end{bmatrix} = \left(\begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} + \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \right) /2 \qquad \textbf{(11)}$$

Where:

$C = Joint\ centre\ in\ 3D$

$L = The\ lateral\ maker\ placement\ on\ joint\ in\ 3D$

$M = The\ medial\ maker\ placement\ on\ joint\ in\ 3D$

3.4.2. Hip Centres

Four new markers (Sacrum, PEL, R_iliac and L_iliac) were created between right & left ASIS (Anterior Superior Iliac Spine) and PSIS (Posterior Superior Iliac Spine) using the previous equation applied to get joint centres (Figure 3.11).

Then, Davis' (1991) method was used to calculate actual hip joint centres on both sides. Predicted C (a function of leg length) through linear regression and hip joint centres on three axes (X_H, Y_H and Z_H) were calculated via:

$$C = 0.115 \times Length_{leg} - 0.0153 \quad \textbf{(12)}$$

$$X_H = S[C \sin\theta - Pelvis] \quad \textbf{(13)}$$

$$Y_H = [-Y_{dis} - R_{marker}] \cos\beta + C \cos\theta \sin\beta \quad \textbf{(14)}$$

$$Z_H = [-Y_{dis} - R_{marker}] \sin\beta - C \cos\theta \cos\beta \quad \textbf{(15)}$$

Where:

$Length_{le}$ = Averaged leg length from both legs. Length of each leg calculated adding the lengths of thigh and shank using marker placement

S = +1 for the right side, -1 for the left side

Pelvis = The marker placement calculated the distance between both ASIS (in meters)

Y_{dis} = Anterior posterior component of the ASIS to hip centre distance (in meters) in the sagittal plane of the pelvis

R_{marker} = marker radius (in meters)

θ = 28.4 ($\pm$6.6) °, the predicted angle from the hip joint centre to each ASIS in the frontal plane (medial-lateral plane)

β = 18 ($\pm$4) °, the predicted angle of pelvic tilt in the sagittal plane

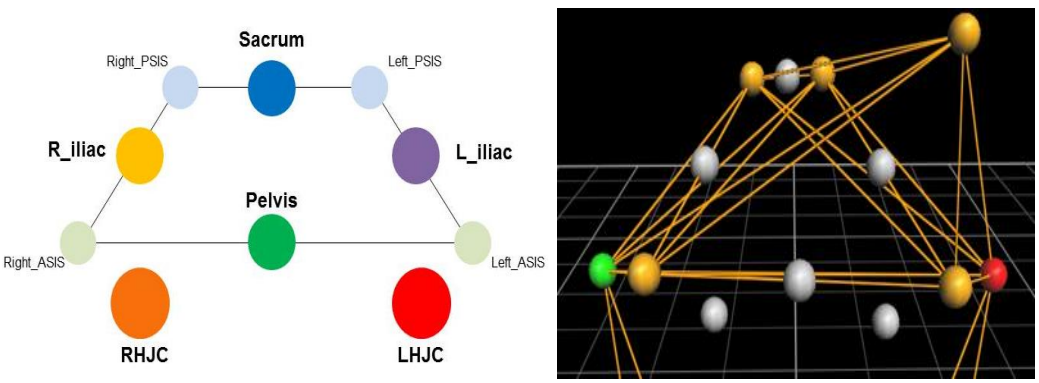


Figure 3.11: Markers on hip (right & left ASIS and PSIS) and six created markers including right & left hip joint centres (RHJC & LHJC). The right picture is showing makers on the hip on Vicon 1.7.1.

3.4.3. Force Plates Centre

To determine the movement of the Stewart platform, a new marker (FPC: Force Plates Centre) at the origin of the force plates was reconstructed from the extra 4 markers attached at the corners of the force plates (Figure 3.12). This FPC marker was used to track the origin of the force plates while the Stewart platform was translating in moving platform trials of the 2nd and 3rd studies. Therefore, the orientation of the force vector and the COP could be adjusted based on the movement of the Stewart moving platform.

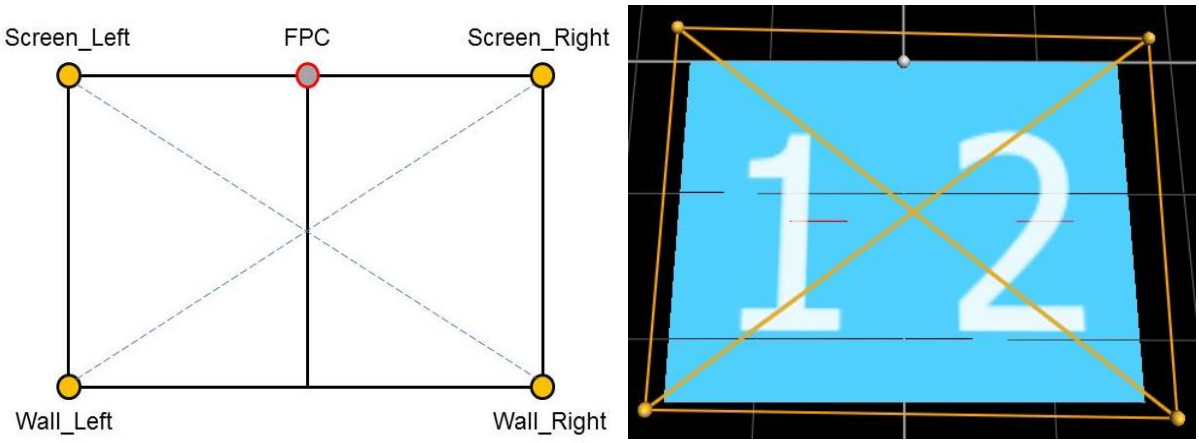


Figure 3.12: Created FPC (Force Plates Centre) gained via using four markers at the edges of the force plates. The right picture is showing markers on the force plates on Vicon 1.7.1.

3.4.4. Centre of Mass (COM) and Body Centre of Mass (BCM) calculations

To get COM of each segment, the calculated distance of mass centre via Yeadon (1990)'s inertia model from proximal joint was applied into the Vicon marker placements:

$$COM = (J_2 - J_1) \times \frac{\mathrm{d}}{l} + J_1 \quad \textbf{(16)}$$

Where:

COM: *Centre of mass for each segment*
J_1: *Distal joint*
J_2: *Proximal joint*
d: *Distance of mass centre from proximal joint (mm)*
l: *Segment length (mm)*

Then, BCM was calculated:

$$\mathrm{BCM} = \sum_{i=1}^{n} \left(\frac{COM_i \times segment\ mass_i}{segment\ mass_i}\right)$$

Numbers of segments were varied to get BCM depending on the foot position. Whole foot was applied as a segment for 'flat' positions and the foot was separated into two parts (toe and rear foot) for 'demi-pointe' positions in the 2nd study. For the 3rd study, the 'flat' position version was applied to calculate BCM.

3.4.4. Centre of Pressure (COP)

The force data were down sampled with an imbedded Finite Impulse Response (FIR) filter from 2000 Hz to 200 Hz. COP_{net} on X and Y axes were calculated from two force plates as in Winter's equation (1995) for the 1st and 2nd studies in which the subjects balanced on the both legs. To calculate the COP_{net} the following equation was used:

$$\mathrm{COP_{net}} = \mathrm{COP_l}\,\frac{\mathrm{R_{vl}}}{\mathrm{R_{vl}} + \mathrm{R_{vr}}} + \mathrm{COP_r}\,\frac{\mathrm{R_{vr}}}{\mathrm{R_{vl}} + \mathrm{R_{vr}}} \qquad \textbf{(17)}$$

Where:

COP_l and COP_r are the COPs under respectively the left and right feet

R_{vl} and R_{vr} are the reaction forces acting respectively on the left and right feet

Standard Deviation (SD), Range, Sway Path, Surrogate and short and long range Detrended fluctuation Analysis (DFA) were determined from the calculated COP_{net}. The Surrogate value was applied to calculate Approximate Entropy (ApEn).

3.4.4.1. Standard Deviation

The Standard Deviation (SD) was calculated from the COP_{net} on X and Y axes according to the following formulas:

$$\mu x = \frac{1}{N}\sum_{i=1}^{N} x_i \quad \textbf{(18)}$$

$$SDx = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu x)^2} \quad \textbf{(19)}$$

$$\mu y = \frac{1}{N}\sum_{i=1}^{N} y_i \quad \textbf{(20)}$$

$$SDy = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \mu y)^2} \quad \textbf{(21)}$$

Where:

N = Number of samples

μx = Mean value of COP_{net} *on x axis*

μy = Mean value of COP_{net} *on y axis*

x_i = COP_{net} *on x axis*

x_y = COP_{net} *on y axis*

3.4.4.2. Range

The $Range_x$ and $Range_y$ of COP_{net} were calculated via:

$$\mathrm{Range_x} = \mathrm{max}_x - \mathrm{min}_x$$

$$\mathrm{Range_y} = \mathrm{max}_y - \mathrm{min}_y$$

Where:

$max_x = the\ maximum\ value\ of\ COP_{net}\ on\ x\ axis$

$min_x = the\ maximum\ value\ of\ COP_{net}\ on\ x\ axis$

$max_y = the\ maximum\ value\ of\ COP_{net}\ on\ y\ axis$

$min_y = the\ maximum\ value\ of\ COP_{net}\ on\ y\ axis$

3.4.4.3. Sway Path

The whole length of COP_{net} trajectory can be represented by using Sway Path. Sway Path uses trigonometry to get the sum of COP_{net} trajectory from distances between every two COP_{net} positions. The following function was used to get Sway path:

$$Sway\ Path = \sum_{i=1}^{N} \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2} \quad \textbf{(23)}$$

Where:

$X_i = the\ series\ of\ COP_{net}\ on\ X\ axis$

$Y_i = the\ series\ of\ COP_{net}\ on\ Y\ axis$

3.4.4.4. ApEn (Approximate Entropy) and Surrogate

This is considered as a 'regularity and complexity statistic' which gives a measurement of the unpredictability of the fluctuations in a time series, for example an instantaneous heart rate (Pincus and Goldberger, 1994). If the time series has many repetitive patterns, ApEn becomes small but a more unpredictable value which

is more complicated shows a higher ApEn (Ho et al., 1997). The range of ApEn values are between 0 to 2 so as the value of ApEn gets closer to 2, the data set is more random (highly complex) (Harbourn and Stergiou, 2003).

However, strong dependence on sequence length and poor self-consistency cause some significant weaknesses in ApEn. Therefore, the result will be different depending on the choice of the pattern length and the criterion of similarity (Ho et al., 1997).

From a given empirical sample of data, the surrogate testing can be applied to determine the nature of the process that generated this sample (Nagarajan, 2006) and the mean, variance and power spectra of surrogate data are the same as the original data (Buzzi et al., 2003). Therefore, the original dataset can be compared with a random data set which is created by a surrogate (Harbourne and Stergiou, 2002) and these data sets can be applied into some nonlinear analyses such as ApEn and Lyapunov Exponet (LyE). Using a surrogate technique allows comparing a random dataset (generated by surrogate testing) and experimental data (Harbourne and Stergiou, 2002).

In the surrogate function, the original time series data (the COP) was used as an input, and then a surrogate model was created from this data. This surrogate model was a new time series data generated from the input and was designed to have exactly the same properties but to be as random as possible (Schreiber and Schnitz, 2000). To begin with, Fast Fourier Transformation (FFT) was applied to COP_{net} data to generate the surrogate data on Matlab. This surrogate data and the original data were used as separated inputs for the Approximate Entropy (ApEn) cited before.

3.4.4.5. DFA (Detrended Fluctuation Analysis)

To get α, the time series of data of length N is integrated with the following formula:

$$\mathrm{y(k)} = \sum_{i=1}^{k}[B(i) - B_{average}] \quad \textbf{(24)}$$

The integrated time series *y*(*k*) is then separated into *n* boxes (intervals). In each box, a local trend is fit to the data in the box.

Afterwards, the root mean square fluctuation function F(n) is calculated from the following formula:

$$\mathrm{F(n)} = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_n(k)]^2} \quad \textbf{(25)}$$

3.4.5. EMG Latencies

To investigate into the reaction time from the stimulus to muscle activations during dynamic posturography, EMG latencies from trials with platform translations were analysed and compared amongst conditions of positions and groups.

From the 2nd study, EMG latencies were calculated between the start of platform movement, based on horizontal forces (Fx and Fy), and the first burst of any major muscles by visual inspection. Manual inspection (visually) is the most common way to get EMG latency (Reaz et al., 2006) and considered as a respectable method (Hodge and Bui, 1996; Boxtel et al., 1993; Tillin et al., 2013). For the 3rd study (one leg standing), EMG latencies were calculated from any muscles which activated after the platform movement. An example of EMG latency is shown in Figure 3.13. Analogue TrignoEMG has 48 ms delay in the system (Delsys, 2009), so it has been subtracted from the EMG latency in both the 2nd and 3rd studies to be accurate. M1 (stretch reflex) from lower legs generally appears within or about 50 ms after a

stimulus as discovered by some researches (Diener et al., 1984; Pertersen et al., 1998; Corden et al., 2000). Also, Horak and Diener (1994) used 500 ms to limit EMG latency from leg muscles. Therefore, EMG latencies from the lower legs (Tibialis-Anterior, Peroneus_Longus, Gastrocnemius) were taken within the range of 50-500 ms only to not include stretch reflex and other muscle activations may have burst thanks to some late corrections which did not happen due to the platform movement (stimulus).

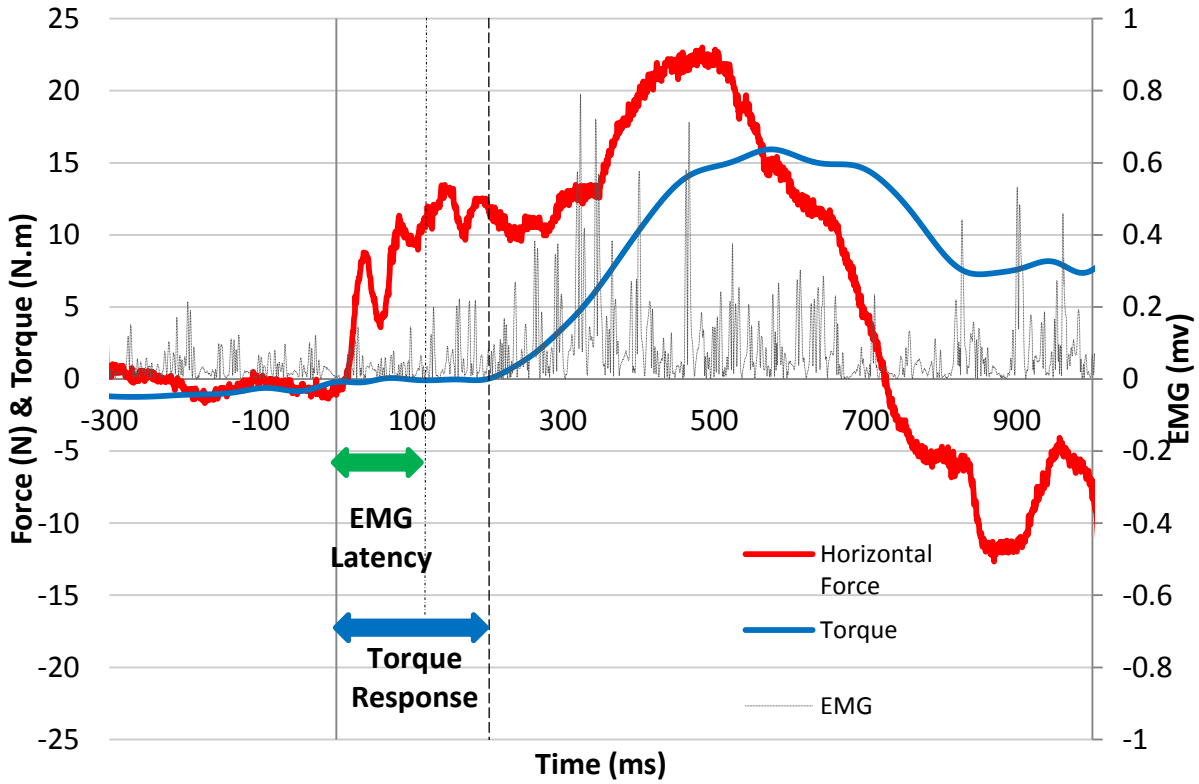


Figure 3.13: An example how to calculate EMG latency and Torque response time from the point where force rises (time = 0) to the EMG burst and Torque rise in ms

3.4.6. 3D Torque

The kinematic and kinetic data were used in 3D inverse dynamics analysis to calculate joint torques in 3D. The 3D inverse dynamics calculations were processed in Matlab R2013B, using functions developed by Blenkinsop (2015) in PhD thesis. The final results of 3D inverse dynamics were expressed in the Global Coordinate System (GCS).

Force in the three axes:

$$\left.\begin{array}{l}\sum F_x = ma_x \\ \sum F_y = ma_y \\ \sum F_z = ma_z\end{array}\right\} \sum \boldsymbol{F} = m\boldsymbol{a} \tag{23}$$

Where:

F: Force (N)

m: Mass (kg)

α: Acceleration (m. s^{-2})

Moment of the first joint in the three axes:

$$\left.\begin{array}{l}\sum M_x = I_x\alpha_x + (I_z - I_y)\omega_y\omega_z \\ \sum M_y = I_y\alpha_y + (I_x - I_z)\omega_z\omega_x \\ \sum M_z = I_z\alpha_z + (I_y - I_x)\omega_x\omega_y\end{array}\right\} \sum \boldsymbol{M} = \boldsymbol{I} \cdot \boldsymbol{\alpha} + \boldsymbol{\omega} \times (\boldsymbol{I} \cdot \boldsymbol{\omega}) \tag{24}$$

Where:

ω: Angular velocity (rad.s^{-1})

α: Angular acceleration of the segment centre of mass (m. s^{-2})

I: Inertia of the segment (kg.m^{-2})

The proximal joint forces were calculated in GCS:

$$\boldsymbol{F}_{ip}^{GCS} = m_i\boldsymbol{a}_i^{GCS} - m_i\boldsymbol{g}^{GCS} - \boldsymbol{F}_{id}^{GCS} \tag{25}$$

Where:

$\boldsymbol{F}_{ip}^{GCS}$ *: the proximal joint force (N)*

$\boldsymbol{F}_{id}^{GCS}$ *: the distal joint force (N)*

$m_i\boldsymbol{a}_i^{GCS}$ *: the mass and acceleration of the segment centre of mass (kg.m.s-2)*

$m_i\boldsymbol{g}^{GCS}$ *: the mass (kg) and the gravity vector*

The proximal joint moments were calculated in the Local Coordinate System (LCS) so the first joint and proximal joint forces previously calculated were converted from the GCS to the LCS.

The distal joint moments were calculated in the LCS:

$$\boldsymbol{M}_{ip}^{LCS} = \dot{\boldsymbol{H}}_i^{LCS} - \boldsymbol{M}_{id}^{LCS} - \left(\boldsymbol{p}_i^{LCS} \times \boldsymbol{f}_{ip}^{LCS}\right) - \left(\boldsymbol{d}_i^{LCS} \times \boldsymbol{f}_{id}^{LCS}\right) \quad \textbf{(26)}$$

Where:

$\mathbf{M}_{\mathrm{ip}}^{\mathrm{LCS}}$: the proximal joint force in LCS

$\mathbf{M}_{\mathrm{id}}^{\mathrm{LCS}}$: the distal joint force in LCS

$\mathbf{f}_{\mathrm{ip}}^{\mathrm{LCS}}$: local force vector of the proximal joint

$\mathbf{f}_{\mathrm{id}}^{\mathrm{LCS}}$: local force vector of the distal joint

$$\dot{\boldsymbol{H}}^{LCS} = \begin{bmatrix} I_x\alpha_x + \left(I_z - I_y\right)\omega_y\omega_z \\ I_y\alpha_y + (I_x - I_z)\omega_z\omega_x \\ I_z\alpha_z + \left(I_y - I_x\right)\omega_x\omega_y \end{bmatrix} \text{ : the moment in LCS (N.m)} \quad \textbf{(27)}$$

$\boldsymbol{p}_i^{LCS}$ *= lever arm from mass centre to proximal joint (m)*

$\boldsymbol{d}_i^{LCS}$ *= lever arm from mass centre to distal joint (m)*

Finally, all the moments in the LCS were transferred to the GCS to analyse and discuss Torque data in the GCS.

3.4.7. Statistics

For each study, different statistical comparisons were used depending on conditions, positions and numbers of groups.

3.4.7.1. The 1st study

All dependent variables calculated from COP_{net} (SD, Range, Sway Path, ApEn and DFA) were compared using 'IBM SPSS Statistic 20' for between ballet shoes conditions and pointe shoes conditions (six comparisons in total) (Figure 3.14) using One-way ANOVA with significant level of 0.05. Paired T test was used to compare ApEn between original data and surrogate data ($p<0.05$). The results and discussion of the 1st study are indicated in Chapter 4.

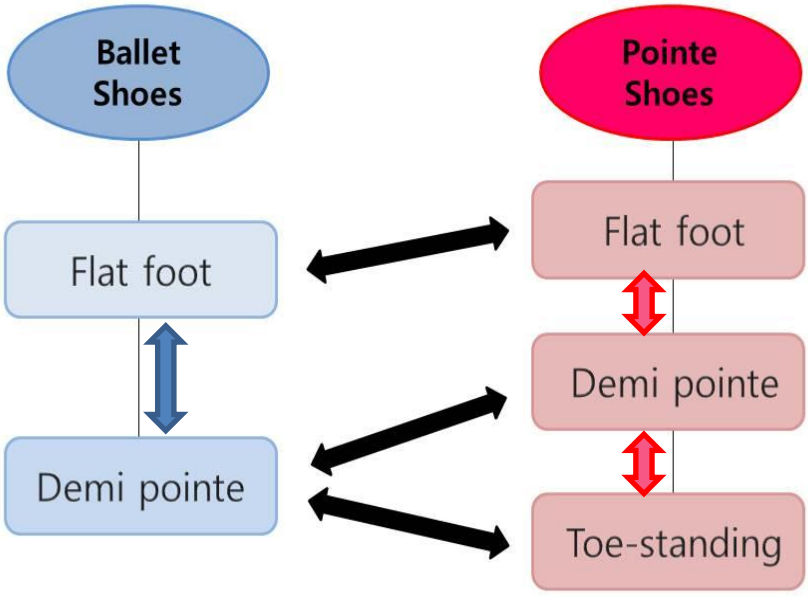


Figure 3.14: Comparisons of five ballet 2nd positions between types of shoes

3.4.7.2. The 2nd study

Means and standard deviation (SD) of EMG latencies from each subject were calculated and One-way ANOVA was used to test significant differences in dance positions (with a significance level of $p<0.05$) using Matlab R2012b (Figure 3.15). Findings based on the 2nd study are discussed in Chapter 6.

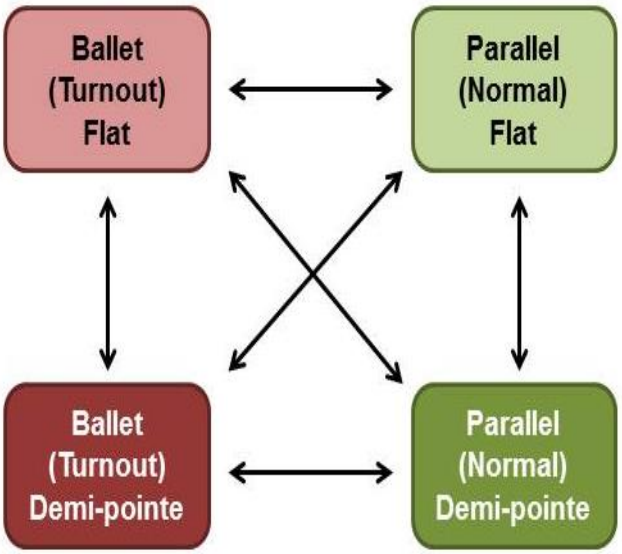


Figure 3.15: Six Comparisons amongst four dance balance conditions in the 2nd study

3.4.7.3. The 3rd study

For the moving platform trials, mean values of EMG latencies and torque response time were compared between groups and within groups using 'IBM SPSS Statistic 20' (with a significance level of $p<0.05$).

A four-way Mixed ANOVA was used to test significances of dependent variables in groups, foot positions, directions of platform movement and speeds of platform movement on the fastest EMG latencies amongst All EMG sensors and three Shank EMG sensors separately. Then, only the quickest EMG latencies amongst three Shank EMG sensors were chosen to be tested in the separated groups by using three-way Repeated Measures ANOVA (foot positions × directions × Speeds). To

compare the fastest Shank EMG latencies of Dancer and Gymnast groups in the same conditions, Independent samples T test was used. One-way Repeated Measures ANOVA was chosen to test each group's the fastest Shank EMG latencies at each speed (Table 3.9). To compare the original ApEn and Surrogate ApEn, Paired T test was used.

Table 3.9: Designs of statistical tests used on mean values of EMG latencies

Statistic Methods	Data Range	Comparisons
4-way Mixed ANOVA	All EMG latencies	- Groups - Foot positions - Directions - Speed
	3 Shank EMG latencies	
3-way Repeated Measures ANOVA	Dancer group 3 Shank EMG latencies	- Foot positions - Directions - Speeds
	Gymnast group 3 Shank EMG latencies	
Independent samples T test	3 Shank EMG latencies at Slow (Dancers vs Gymnasts)	- At each condition of 'Foot positions × Directions' e.g. 'Dancer Normal Forward Slow' vs 'Gymnast Normal Forward Fast'
	3 Shank EMG latencies at Fast (Dancers vs Gymnasts)	
1-way Repeated Measures ANOVA	3 Shank EMG latencies Dancer group at Slow	- Comparisons amongst 8 conditions (2 Foot positions × 4 directions) e.g. 'Normal Forward' vs 'Turnout Lateral'
	3 Shank EMG latencies Dancer group at Fast	
	3 Shank EMG latencies Gymnast group at Slow	
	3 Shank EMG latencies Gymnast group at Fast	

Four-way, three-way ANOVA, two-way ANOVAs and Independent T Test were used to test significances of variables from the quickest Torque response and One-way ANOVA was used to compare the groups in each condition of 'Foot positions × Directions × Speeds' (Table 3.10).

Table 3.10: Designs of statistical tests used on mean values of Torque response time

Statistic Methods	Data Range	Comparisons
4-way Mixed ANOVA	Among All Torque Joints	- Groups - Foot positions - Directions - Speed
	Among Main Torque axis	
3-way Repeated Measures ANOVA	Dancer group (All Torque, Main Torque)	- Foot positions - Directions - Speeds
	Gymnast group (All Torque, Main Torque)	
2-way Repeated Measures ANOVA	Dancer group Normal Foot (All Torque, Main Torque)	- Directions - Speeds
	Dancer group Turnout Foot (All Torque, Main Torque)	
	Gymnast group Normal Foot (All Torque, Main Torque)	
	Gymnast group Turnout Foot (All Torque, Main Torque)	
Independent samples T test	Among All Torque Joints (Dancers vs Gymnasts)	- At each condition of 'Foot positions × Directions' e.g. 'Dancer Normal Forward Slow' vs 'Gymnast Normal Forward Fast'
	Among Main Torque axis (Dancers vs Gymnasts)	
1-way ANOVA	Every Single Joint Torques (9 Torques) (Dancers vs Gymnasts)	- At each condition of 'Foot position × Directions × Speeds' e.g. 'Dancer Turnout Forward Fast' vs 'Gymnast Turnout Forward Fast'

Non-parametric test and frequency order test were undertaken by using EMG latencies from the three Shank muscle (TA: Tibialis Anterior, PL: Peroneus Longus and GA: Gastrocnemius) to check effects of foot positions and directions and speeds of platform movements on the order activations amongst those muscles. 'IBM SPSS Statistic 20' was used to run non-parametric test.

For frequency order test, orders of EMG onset were marked from each trial. Then, numbers of the 1st, 2nd and 3rd onsets (muscle reactions in the order amongst three Shank muscles) were counted from all trials depending on groups, foot positions, directions and speeds as well as total groups. Depending on the highest total number, each muscle was considered that the muscle has reacted the same as the orders of highest numbers (Table 3.11). Also, two types of percentages ($\%_A$ & $\%_B$) were calculated which were related to each frequency orders. $\%_A$ is the percentage of probability to have No. 1 (the 1st reaction muscle amongst three Shank muscles) and %B is the percentage of probability to have the 1st, 2nd or 3rd frequency order depending on the muscles (Table 3.12).

The main reason why both Non-parametric and frequency order test were done and discussed together is because Non-parametric test might standardise downward the characteristic of EMG latencies orders at each condition. Non-parametric test only considers mean value of EMG latencies from three trials at each condition from each subject (e.g. mean value of three Normal foot + Forward + Slow from Dancer 1). Then calculate the orders by comparing mean values of all subject (or two groups separately) from the minimum to maximum at each condition. Therefore, the orders of EMG latencies onset may be slightly different to the frequency orders which are counted from every single trial. Also an advantage of using frequency order test is the orders can be compared by percentages which show probabilities to react in the orders.

SD, Range, Sway Path, ApEn and DFA of COP (not COP_{net} as this study only measured balance on one leg) were used as dependent variables for the static trials and two-way ANOVA and Paired T Test were used to test significance level ($p < 0.05$).

Table 3.11: An example of counting Frequency orders in Turnout Backward at Slow from a group (the 1st reaction muscle: in Red, the 2nd reaction muscles: in Orange & the 3rd reaction muscle: in Yellow at the bottom part of this table)

Trials	Subjects No.	TA in order	PL in order	GA in order
1st Trials	Sub 1	3	1	2
	Sub 2	3	2	1
	Sub 3	2	3	1
	Sub 4	3	2	1
	Sub 5	1	3	2
	Sub 6	1	3	2
	Sub 7	2	3	1
	Sub 8	3	1	2
2nd Trials	Sub 1	3	2	1
	Sub 2	3	1	2
	Sub 3	3	1	2
	Sub 4	1	3	2
	Sub 5	3	2	1
	Sub 6	3	1	2
	Sub 7	1	3	2
	Sub 8	1	2	3
3rd Trials	Sub 1	2	1	3
	Sub 2	3	2	1
	Sub 3	1	3	2
	Sub 4	2	1	3
	Sub 5	3	2	1
	Sub 6	3	1	2
	Sub 7	3	1	2
	Sub 8	3	1	2
Total No. '1'		6	**10**	8
Total No. '2'		4	7	**13**
Total No. '3'		**14**	7	3
All 24 in total (3 ×8 =24), Total frequency order is PL - GA - TA				

Table 3.12: An example of calculating $\%_A$ and $\%_B$ based on Total Numbers of each muscle from Table 3.10 ($\%_A$: in Blue, $\%_B$: in Green)

Total No. Reaction orders	TA	PL	GA
Total No. '1'	6	**10**	8
% of No. '1'	25 $\%_A$	**41.67** $\%_A$, $\%_B$	33.3 $\%_A$
Total No. '2'	4	7	**13**
% of No. '2'	16.67	29.17	**54.16** $\%_B$
Total No. '3'	**14**	7	3
% of No. '3'	**58.33** $\%_B$	29.17	12.5
		e.g. % of No. '1' PL = 10 / 24 × 100 = 41.67 %	

CHAPTER 4

BALLET 2ND POSITION IN STATIC CONDITIONS

Results and discussions of 'the 1st study: A balance study into ballet 2nd position between two types of shoe' is included in this chapter.

This research is related to research questions One, Two and Four:

- Q1. What differences in balance performance are there in different ballet positions and shoe types using multiple balance metrics?

- Q2. What are the main characteristics of balancing on pointe shoes and do types of those affect balance?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

4.1. Standard Deviations about the X axis, Medial-Lateral (SD_X)

There were some significant differences found between different feet positions (BF vs BD, PF vs PD) but not between shoes as indicated by the Standard Deviations along the Medial - Lateral (ML) axis (SD_X) (Table 4.1). These significances are likely due to Flat and Demi-pointe positions not only having different total contact areas but also changes in the activated musculature and joint ranges of motion. This result is also supported by comparing differences between means (Ballet shoes [BD-BF]: 1.36 mm & Pointe shoes [PD-PF]: 1.65 mm > Flat [PF-BF]: 0.04 mm & Demi-pointe [PD-BD]: 0.32 mm).

SD_X between means of BD and PT was not significant (p=0.054) but the mean of PT was larger than the mean of BD (4.33 mm > 3.38 mm). Significances of 'BD vs PT' from SD_X is closer to the significance level than 'PD vs PT' from SD_X (0.054 < 0.128) and means of Pointe shoes are also higher than Ballet shoes. These results indicate

that Pointe shoes drive ML balance to be more varied compared to Ballet shoes and probably cause dancers to have more difficulties to balance than when they are wearing ballet shoes.

Table 4.1: Means and SD of Standard Deviations on X (ML) axis (SD_X) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05)

SD_X (mm)		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	2.02	2.06	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	0.75	0.92	0.808		
Demi-Pointe	Mean	3.38	3.70	**BD vs PD**	**0.000***	**0.001***
	SD	0.80	0.98	0.204		
Toes (Pointe)	Mean		4.33	**BD vs PT**		**PD vs PT**
	SD		1.54	0.054		0.128

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

4.2. Standard Deviations about the Y axis, Anterior-Posterior (SD_Y)

'BD vs PT' (p=0.034), 'BF vs BD' (p=0.026) and 'PD vs PT' (p=0.014) were significantly different in Anterior - Posterior (AP) direction of Standard Deviations (SD_Y) (Table 4.2). Wearing Pointe shoes may affect SD_Y to have greater differences between Demi-pointes (BD & PD) and PT because the Base of Support (BOS) becomes smaller on tip toes with Pointe shoes in the AP direction (Y axis) compared to two Demi-pointe positions. Also, the mean of SD_Y from PT (2.52mm) is a lot smaller than any others means of SD_Y because of the small size of BOS with tip of Pointe shoes.

One of the interesting findings is that there is longer BOS in the AP direction with Flat position than in Demi-pointe but the mean variation is still smaller in the Flat positions. There is no chance of going outside BOS in Flat feet and this means that fluctuation is in COP so it could be lager and they not fall. In Demi-pointe, dancers

have a smaller BOS so it is expected to have smaller fluctuations as could go outside BOS and then dancers will lose balance. Therefore, it is harder for the balance system to control balance on Demi-pointe. Moreover, the ankle joints may be less stable, the feet arches may have motion, the feet muscles may fatigue more or have poorer control etc.

Table 4.2: Means and SD of Standard Deviations on Y (AP) axis (SD_Y) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05)

SD_Y (mm)		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	3.92	4.04	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	0.93	0.76	0.611		
Demi-Pointe	Mean	4.54	4.46	**BD vs PD**	**0.026***	0.082
	SD	1.03	0.96	0.710		
Toes (Pointe)	Mean		2.52	**BD vs PT**		**PD vs PT**
	SD		0.96	**0.034***		**0.014***

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

As the mean of Pointe (Toes) SD_Y is the smallest, this can be due to the contact point being so small that if the motion is larger than it would move outside BOS and lose balance. This could also show that in Flat and Demi-pointe, the maximum control to keep motion to a minimum stability that could be used was not being used and only enough to keep them stable was being used. If dancers can wobble less on Pointe then unless this is in some way more mechanically stable. Otherwise, dancers could maybe have some wobbled less in Flat and Demi-pointe if they have really been made to (due to training).

4.3. Range about the X axis of the COP, Medial-Lateral ($Range_X$)

There are few significant interactions found between shoes and feet positions from Medial - Lateral direction of Range ($Range_X$) (Table 4.3). Both Ballet and Pointe shoes had significant differences between their feet positions (both p=0.001).

Comparing means of RangeX, Pointe shoes seem to allow a larger range of movement in ML to control balance than Ballet shoes in standing on Demi-pointe. The mean of Range gets much greater on PT (31.97mm) compared to BD or PD because dancers seems to move COP side to side to control balance on Pointe (tip toe) by plantar flexing at the ankles. Also 'BD vs PT' (p=0.033) and 'PD vs PT' (p=0.009) had significant values.

Table 4.3: Means and SD of Range on X (ML) axis ($Range_X$) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05)

$Range_X$ (mm)		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	15.93	15.15	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	5.78	7.33	0.631		
Demi-Pointe	Mean	23.77	25.27	**BD vs PD**	**0.001***	**0.001***
	SD	5.35	6.88	0.430		
Toes (Pointe)	Mean		31.97	**BD vs PT**		**PD vs PT**
	SD		10.84	**0.033***		**0.009***

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

4.4. Range on about the Y axis, Anterior-Posterior ($Range_Y$)

Means of $Range_Y$ between two types of shoes are similar depending on feet positions but different between feet positions, the means of Demi-pointe positions (BD & PD) are greater than Flat positions (BF & PF). A significant value was found from 'BF vs BP' (p=0.040) but the p value between PF and PD was not significant (p=0.05) but really close to the significant level.

Table 4.4: Means and SD of Range on Y (AP) axis ($Range_Y$) from COP_{net} with different types of shoes and feet positions (Sig. < 0.05)

$Range_Y$ (mm)		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	23.31	23.51	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	5.84	3.52	0.902		
Demi-Pointe	Mean	26.87	26.37	**BD vs PD**	**0.040***	0.050
	SD	5.46	4.84	0.660		
Toes (Pointe)	Mean		14.59	**BD vs PT**		**PD vs PT**
	SD		3.99	**0.006***		**0.003***

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

Interestingly, the mean of PT is much smaller (14.59mm) than other means and there are significant differences comparing with PT: 'BD vs PT' (p=0.006) and 'PD vs PT' (p=0.003). These findings support that balancing on Toes restricts range of COP (Centre of Pressure) in AP direction because of small size of pointe shoes tips which make smaller BOS in AP. Instead, dancers move COP in MP more than AP to control their balance on Pointe (Mean PT - $Range_X$: 31.97mm > $Range_Y$: 14.59mm).

4.5. Sway Path

Significances are found only from comparisons of feet positions: 'BF vs BD' (p=0.006) and 'PF vs PD' (p=0.001) (Table 4.5). Sway Path is longer from Demi-pointe position than Flat position in both types of shoes. Standing on Demi-Pointe is generally considered more difficult than standing on Flat feet.

Nevertheless PT is the hardest balance; the mean of Sway Path from PT is the shortest (4399 mm) compared to other shoes and foot positions. This finding is unsurprising as PT COP trajectories in a single direction at a time cannot be longer than in other conditions because the size of BOS is smaller. To have an equivalent length sway path they would have to have a lot fast motions, rapidly changing

direction and as balance control has a delay this would be very difficult to control reactively. Therefore, dancers may have to make only small corrections and thus have a very 'static' control of balance; otherwise, they will need to come down from Pointe. There were no significances in comparisons with PT in statistical analyses.

Table 4.5: Means and SD of Range from Sway Path with different types of shoes and feet positions (Sig. < 0.05)

Sway Path (mm)		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	4587	4568	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	970	977	0.477		
Demi-Pointe	Mean	4815	4803	**BD vs PD**	**0.006***	**0.001***
	SD	869	923	0.698		
Toes (Pointe)	Mean		4399	**BD vs PT**		**PD vs PT**
	SD		1199	0.311		0.318

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

4.6. $ApEn_X$

In order to compare $ApEn_X$ mean values amongst feet positions, the order is PF < BF < PT < PD < BD from the smallest to the largest (Table 4.6). There are significant differences between BF and BD as well as between PF and PD and it means that BD and PD have more unpredictable values than BF (p=0.008) and PF (p=0.003) respectively. These findings indicate that the influence of Demi-pointe feet positions to balance to be more complicated in Medial and Lateral (ML) direction than Flat feet positions as Dancers have to control an additional pair of Metatarsophalangeal (MTP) joints. The significant differences from T-test between Original ApEn (O) and Surrogate ApEn (S) show that every single Original ApEn is less random and more predictable than Surrogate ApEn.

Pointe shoes make balance more repetitive and predictable than Ballet shoes in ML direction as $ApEn_X$ mean values are smaller in Pointe shoes than Ballet shoes. This

may be caused by the solid soles and the toe boxes of pointe shoes. Pointe shoes probably disturb nature movement of MTP joints, which is slightly less predictable than with Pointe shoes on, and probably Ankle joints as well because of tied ribbons around the Ankles.

Table 4.6: Means and SD of Range from $ApEn_X$ with different types of shoes and feet positions (Sig. < 0.05)

		Ballet Shoes			Pointe Shoes			Between Shoes Sig.	Between Positions Sig.	
		O	S	T test	O	S	T test			
Flat	M	**1.381**	1.499	**.000***	**1.374**	1.490	**.000***	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	**0.180**	0.208		**0.184**	0.214		.262		
Demi-Pointe	M	**1.497**	1.585	**.000***	**1.482**	1.569	**.000***	**BD vs PD**	**.008***	**.003***
	SD	**0.114**	0.118		**0.130**	0.145		.365		
Toes (Pointe)	M				**1.415**	1.490	**.000***	**BD vs PT**		**PD vs PT**
	SD				**0.224**	0.224		.320		.393

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes, M: Mean, O: Original ApEn, S: Surrogate ApEn)

There is non-significant difference in comparisons with PT but an interesting fact is that PT has more repetitive patterns than PD and is less predictable than PF in ML direction. Because Dancers control balance in ML direction by pointing their feet even more (Plantar flexion) while they are standing on PT, it might be the major cause of being more predictable compared to PD. However, this study is based on double leg stance so this finding might be different to the result of $ApEn_X$ on single leg PT. It will be interesting to research into single leg stance balance on Pointe but standing on Pointe for a long time (minimum 30 sec) can be challenging for even

professional Ballerinas. Nevertheless, it can be possible to test on professionals only.

4.7. $ApEn_Y$

Non-significance is found in comparisons of $ApEn_Y$ Anterior-Posterior (AP) direction (Table 4.7). The order from the smallest $ApEn_Y$ is PT < PF < BF < BD < PD which is slightly different to $ApEn_X$. PT has the most repetitive patterned balance and PD has the most unpredictable patterns compared to other feet positions.

Table 4.7: Means and SD of Range from $ApEn_Y$ with different types of shoes and feet positions (Sig. < 0.05)

		Ballet Shoes			Pointe Shoes			Between Shoes Sig.	Between Positions Sig.	
		O	S	T test	O	S	T test			
Flat	M	**1.331**	1.527	**.000***	**1.324**	1.525	**.010***	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	**0.172**	0.213		**0.173**	0.214		.413		
Demi-Pointe	M	**1.365**	1.537	.116	**1.367**	1.546	.642	**BD vs PD**	.069	.059
	SD	**0.130**	0.166		**0.133**	0.157		.809		
Toes (Pointe)	M				**1.290**	1.475	.794	**BD vs PT**		**PD vs PT**
	SD				**0.213**	0.292		.290		.304

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes, M: Mean, O: Original ApEn, S: Surrogate ApEn)

Pointe shoes do not seem to make balance pattern more predictable than Ballet shoes in AP direction on Demi-pointe (PD > BD). This finding might be caused

because Dancers depend more in ML direction to control balance than in AL direction during Demi-Pointe and Pointe balance. Therefore, Pointe shoes probably do not affect balance in AP direction to change natural patterns of Demi-pointe balance and even makes it a bit less predictable.

T-test between original $ApEn_Y$ (O) and Surrogate $ApEn_Y$ (S) shows that original ApEn of BD, PD and PT are not always more predictable than Surrogate ApEn in AP direction (P>0.05). Even if the values of original ApEn did not really increase from Demi-Pointe positions (even less from PT) compared to Flat positions, there might be very sensitive changes in these more difficult positions (BD, PD and PT) that may sometimes make the balance control (e.g. COP) more difficult to predict compared to random value (surrogate).

4.8. DFA_X

There is no significant difference in comparisons of DFA_X (Table 4.8). All feet positions have mean values of α within a range between 0.5 and 1 so the correlation of all the positions is 'Correlated' which has a persistent long-range power-law correlations of data.

Table 4.8: Means and SD of Range from DFA_X Long Range with different types of shoes and feet positions (Sig. < 0.05)

		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	0.703	0.703	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	0.149	0.150	0.995		
Demi-Pointe	Mean	0.752	0.805	**BD vs PD**	0.493	0.082
	SD	0.126	0.128	0.375		
Toes (Pointe)	Mean		0.873	**BD vs PT**		**PD vs PT**
	SD		0.145	0.089		0.274

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

4.9. DFA_Y

Table 4.9 indicates that significant differences are found in comparisons of 'BF vs BD' (p=0.021), 'PF vs PD' (p=0.012), 'BD vs PT' (p=0.037) and 'PD vs PT' (p=0.008) from DFA_Y.

Values of α from BF, PF and PT show that data is 'Anti-correlated' (α < 0.5) that means large and small values are alternating in data. Other two positions, which are significantly different to those three 'Anti-correlated' positions, are in a range between '1/f-noise (Pink noise, α = 1)' and 'Non-stationary (Unbounded, α > 1)' correlations (PD: α=1.03) or in 'Corrected (α < 1)' (BD).

Table 4.9: Means and SD of Range from DFA_Y Long Range with different types of shoes and feet positions (Sig. < 0.05)

		Ballet Shoes	Pointe Shoes	Between Shoes Sig.	Between Positions Sig.	
Flat	Mean	0.410	0.310	**BF vs PF**	**BF vs BD**	**PF vs PD**
	SD	0.546	0.670	0.599		
Demi-Pointe	Mean	0.914	1.030	**BD vs PD**	**0.021***	**0.012***
	SD	0.178	0.193	0.220		
Toes (Pointe)	Mean		0.386	**BD vs PT**		**PD vs PT**
	SD		0.511	**0.037***		**0.008***

(BF: Ballet Shoes on Flat, BD: Ballet Shoes on Demi-Pointe, PF: Pointe shoes on Flat, PD: Pointe shoes on Demi-Pointe, PT: Pointe shoes on Toes)

4.10. Discussions

The related research questions are:

- Q1. What differences in balance performance are there in different ballet positions and shoe types using multiple balance metrics?

- Q2. What are the main characteristics of balancing on pointe shoes and do types of those affect balance?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

Dancers may change their main direction of balance control during Turnout positions depending on feet positions. Plantarflexion and dorsiflexion of ankle joints happen by rotating a simple hinge joint in the sagittal plane of the body when the feet are parallel, as a result, standing on double legs (normal feet position which is parallel) has greater stability in ML direction (frontal plane) than in AP direction (the sagittal plane) (Collins & Luca, 1993).

Nolan & Kerringan (2004) researched into balance control depending on three feet conditions (Flat, Half toes and Demi-pointe) during double legs standing. This research found that standing on toes (two conditions) have significantly greater activity (less stable) compared to standing on Flat during short-term balance activities (open-loop control). Therefore, the absence of feedback causes greater balance resistance and correction during sudden perturbations or balancing postures. However, using closed-loop control (long-term region and having feedback), Demi-pointe does not show significantly lower stochastic activity compared to Flat in ML. Increased activity may be related to falls and balance problem so Demi-pointe, which has decreased activity, may be stable with feedback (long term) in ML compared to Flat and compared to its short-term condition. This finding from Nolan & Kerringan's research (2004) contradicts the results from the 1st study (Chapter 4). Long-term period balance control was measured in the 1st study and Demi-pointe has larger corrections and complex balance control in both ML and AP directions. These

different findings may be due to different feet positions (Nolan & Kerringan: Normal feet, the 1st study: Turnout feet the 2nd ballet position).

Therefore, Turnout position on double legs may increase the amount of balance corrections by using feedback in ML direction as well as in AP. Having continual planterflexion and dorsiflexion joints on double legs Demi-Pointe (also on Toe-pointe) will make humans have a greater balance control in ML direction than in Flat Turnout position or/and Normal Demi-pointe. Also, Demi-pointe position uses another segment (a foot is separated in two: toes and foot) and joint (metatarsal) on each standing leg and the turned out metatarsal, ankle, knee and hip joints will allow dancers to sway in ML (by using the joints as sagittal axes). By increasing balance control in ML, balance correction (e.g. COP trajectory, Sway) in AP might be reduced (compensation) so this is possibly a characteristic balance strategy of Turnout Demi-pointe double legs standing and it can be also because of size of BOS which spreads more in ML than in AP.

Moreover, standing on Toe-Pointe may enhance having more frequent and larger range of plantarflexion and dorsiflexion with Turnout position in ML direction. Results from the 1st study explain that dancers need to sway in ML direction even more than in AP to control their balance on Toe-Pointe. Dancers aim to do more plantarflexion on Toe-Pointe (Demi-pointe as well) to be able to stand high but stable. However, there is limitation as to make plantarflexion continuously dancers have to perform a small dorsiflexion once they have reached the maximum of plantarflexion and then try to do plantarflexion again. This process will be repeated by both feet. Yet, the movement of both feet might not be perfectly synchronised so dancers may have to perform plantarflexion on both feet (Toe-Pointe) with a slight time difference. This may be the reason why dancers have increased Range and SD and perform more predictable postural control in ML direction but have smallest movement in AP.

A similar finding was reported by Lin et al. (2005) which investigated into ankle biomechanics of ballet dancers during relevé performance on pointe (in the 1st position, which is on turnout of both feet with both heels touching and knees together, dancers start doing demi-plié and quickly standing on pointe). This research found that ankle joint moment patterns and time to peak moment from dominant and non-

dominant sides were different even though ankle movement patterns from both sides were highly correlated. It was explained from their research that the ankle joints from both sides may have different roles while dancers are performing balance control in relevé on pointe. However, it is unclear if the differences are caused by only ankles movement roles, injuries, imperfect skills or combinations of these reasons. Lee et al. (2012) talked about 'load avoidance strategy', which injured dancers may have adopted after being injured, and Dancers with ankle injury may need to train neuromuscular control around the ankle joints for a good landing to avoid recurring injuries. Training ankle dorsiflexion with one foot, plantarflexion with the other foot for coincident movements and training control of both feet movements at the same time with using rhythm & timing may improve coordination of relevé on double legs pointe Lin et al. (2005).

Despite the largest area of Range and SD in ML, Toe-pointe position has the smallest Sway path. This seems to be caused by the smallest BOS, narrow Pointe shoes platform. Dancers will fall if they perform large amounts of balance correction on Toe-Pointe and this may be the reason why dancers have to do small corrections.

More details involving other studies on answering research questions are written (especially Q4) in Chapter 10.

CHAPTER 5

EMG LATENCIES FROM DOUBLE LEG STANCE DANCE POSITIONS

This Chapter includes findings and discussions of the 2nd study: 'Balance control and response to perturbations whilst standing on both legs in dance positions using a moving platform'.

This research is related to research question Three and Four:

- Q3. Are balance strategies related to dance positions (Turnout versus Normal and/or level of difficulty (flat feet versus demi-pointe)?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

Although multiple muscles were measured with EMG only the fastest EMG latencies were analysed for this thesis. More details on data collection procedures are described in Chapter Three.

5.1. The Fastest EMG Latencies amongst Six Shank EMG Sensors

EMG latencies from six EMG sensors on both shanks, two Tibialis Anterior (TA), two Peroneus Longus (PL) and two Gastrocnemius (GA), were analysed depending on four feet positions (NF: Normal Flat, ND: Normal Demi-pointe, TF: Turnout Flat & TD: Turnout Demi-pointe). Mean and SD of EMG latencies in four different feet positions are shown in Table 5.1 & Figure 5.1.

Overall, Demi-pointe positions have longer delays than Flat positions based on the group mean values. There are some significant differences between Flat and Demi-pointe (Sig. < 0.05, p=0.000 or p=0.001) but not within Flat positions and within Demi-pointe positions. The differences of the means within Flat and Demi-pointe positions were 42.29 ms (NF vs ND, p=0.001) and 48.76 ms (TF vs TD, p=0.000).

There is no significance between NF and TF (p=0.057) but the mean of EMG latency from NF is greater than TF. Also, each subject has longer EMG latency from NF than TF apart from one subject. Therefore, more significant difference may have been possibly found if there were more subjects.

Table 5.1: Means and SD of EMG latencies (in ms) with different feet positions (Sig. < 0.05)

	Normal Flat (a)	Normal Demi-pointe (b)	Turnout Flat (c)	Turnout Demi-pointe (d)
Sub 1	78.76	163.04	100.19	120.77
Sub 2	105.08	129.68	76.37	137.76
Sub 3	87.51	112.09	63.20	115.11
Sub 4	99.38	146.46	74.18	138.08
Sub 5	121.07	145.50	119.24	159.39
Sub 6	74.88	100.68	61.43	93.44
Sub 7	87.63	135.44	61.65	136.25
Sub 8	101.43	161.19	90.73	136.21
Mean ± SD	94.47 ± 15.21	136.76 ± 22.10	80.87 ± 20.93	129.63 ± 19.67
Sig (p<0.05)	b **0.001***	a **0.001***	a 0.057	a **0.000***
	c 0.057	c **0.000***	b **0.000***	b 0.311
	d **0.000***	d 0.311	d **0.000***	c **0.000***

(Normal Flat [NF]: Parallel position {used in contemporary dance} on Flat feet, Normal Demi [ND]: Parallel position on Demi-Pointe, Turnout Flat [TF]: Ballet 2nd position on Flat feet, Turnout Demi [TD]: Ballet 2nd position on Demi-Pointe)

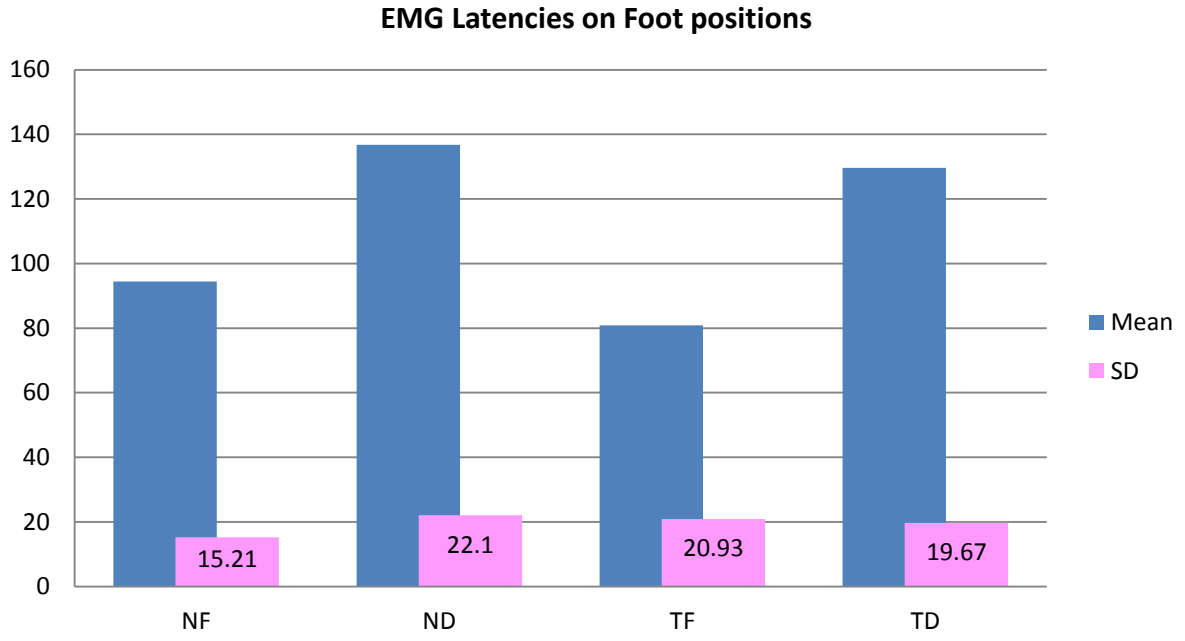


Figure 5.1: Mean graphs of EMG Latencies (ms) from each foot position (NF: Normal Flat, ND: Normal Demi, TF: Turnout Flat, TD: Turnout Demi)

5.2. Discussions

The related to research questions are:

- Q3. Are balance strategies related to dance positions (Turnout versus Normal and/or level of difficulty (flat feet versus demi-pointe)?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

EMG activity contains 'M1' (monosynaptic transmission & stretch reflex: under 40 ms but no earlier than 30 ms), 'M2 & M3 combination' (pre-programmed reactions & long-latency reflexes: there are 2 peaks between 50 and 100 ms) responses and 'voluntary reaction' after having a sudden load or perturbation (Latash, 2008). These times might be based on arm muscles so EMG latencies from legs might be longer as it takes time to travel to CNS. Horak et al. (1989) classified EMG latency into 3

separated parts the first (0-75 ms), second (75-150 ms) and following activation for EMG activity from leg muscles as M1, M2 & M3 combination responses and voluntary reaction.

From the 2nd study, both Normal feet positions have EMG latencies under 100 ms (NF: 94.47 ms & TF: 80.87 ms). These EMG latencies are possibly within M2 & M3 actions so Flat positions may allow dancers to perform pre-programmed reactions & long-latency reflexes in order to control their balance after perturbation. On the other hand, Demi-point positions have longer EMG latencies (significantly different) than Flat positions (FD: 136.76 ms & TD: 129.63 ms) and these are over 100 ms. Therefore, Demi-pointe positions may be performed by both voluntary reaction as well as M2 & M3 combination.

It can be inferred from these results from the 2nd study that EMG latencies get shorter if the balance position becomes easier (e.g. Flat positions) than harder (e.g. Demi-pointe positions). The muscles of the shank may be already working with a small amount of activations to keep standing up right on Demi-pointe positions even before balance is being perturbed. Therefore, EMG latencies on Demi-pointe positions can be longer than on Flat positions because it may take a longer time to react against stimulus (platform movement) as CNS is probably sending information already to keep correcting quiet standing balance on Demi-pointe. Moreover, dancers might be familiar with Turnout positions as EMG latencies are slightly shorter than the relevant Normal foot positions.

A number of researchers have found EMG latencies around M2 & M3 durations. Diener et al. (1984) found 108-123 ms from triceps surae (GA + Soleus) and 103-113 ms from TA after having a platform tilt. Horak et al. (1989) found 100 ms of EMG latency from GA after having a platform movement. Moor et al (1988) reported around 101 ms of GA and 110 ms of TA EMG latencies after having an angular range of activity.

The reason why EMG latencies from the 2nd study are shorter than in previous researches may be because PL was used as another EMG sensor attachment

(normally only TA and GA have been used) in this study. Also this might be one of the reasons why EMG latencies of Turnout positions are shorter than Normal positions as PL needs to be used more to control balance on Turnout double leg standing position than on Normal double leg standing positions. Meanwhile, balancing on Turnout position may be easier for dancers (especially ballet dancers) as they train dance with turnout feet or foot. All eight subjects had many years of ballet training even if they also danced Jazz and Contemporary dance too. Lastly, turnout stance might help the human body to balance more comfortably without having too much control.

More details with other studies on answering research questions are written (especially Q4) in Chapter 10.

CHAPTER 6

EMG LATENCIES FROM SINGLE LEG BALANCE IN DYNAMIC CONDITIONS

This Chapter shows the results and discussions of EMG latencies from single leg balance in dynamic conditions from the 3rd study: Comparisons of balance control and response to perturbations in single leg standing dance positions between Dancers and Gymnasts. More information about research design, procedures and statistical analyses of the 3rd study are explained in Chapter 3.

This Chapter 6 is linked to research question Four, Five, Six and a part of Three:

- Q3. Are balance strategies related to dance positions (Turnout versus Normal) and/or level of difficulty (Flat feet versus Demi-Pointe)?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

6.1. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on both Dancer and Gymnast Groups

A four-way mixed ANOVA was run on the fastest EMG latencies of All EMG (amongst 11 sensors) and Shank EMG (amongst three sensors) separately. Differences of mean values between All EMG and Shank EMG are compared in 6.1.

6.1.1. Dancer Group vs Gymnast Group

Without considering all independent variables (foot positions, directions and speeds), the Gymnast group has longer mean EMG latencies compared to the Dancer group, 2.61 ms from All EMG and 4.97 ms from Shank EMG longer (Table 6.1 & Figure 6.1). However, no significance difference was found between groups from both All EMG and Shank EMG.

Mean values of Shank EMG are longer in both Dancer (2.81 ms) and Gymnast (5.17 ms) groups compared to All EMG. It can be inferred that there are some cases where other parts of body were reacted quicker than lower leg from the subjects.

Table 6.1: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Dancer and Gymnast groups

		Dancer Group	Gymnast Group	Sig.
All EMG	**Mean**	120.82	123.43	0.608
	SE	3.52	3.52	
Shank EMG	**Mean**	123.63	128.60	0.311
	SE	3.34	3.34	

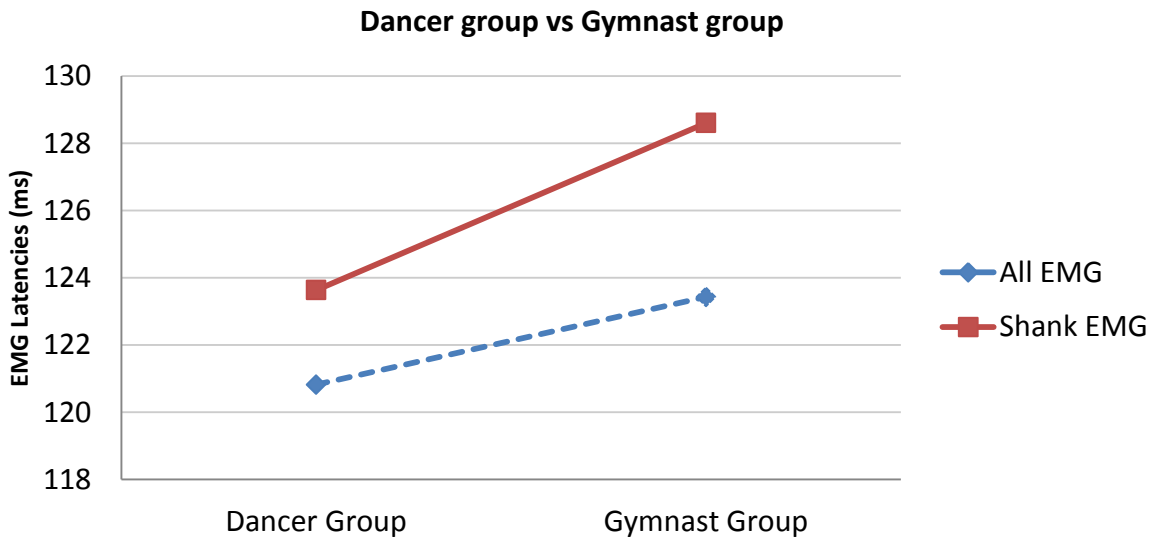


Figure 6.1: Mean graphs of All and Shank EMG Latencies (ms) with comparing Dancer and Gymnast groups

6.1.2. Foot Positions

The fastest EMG latencies of All EMG is significantly different between Normal and Turnout foot positions (p=0.034) and in Normal foot All EMG is longer than Turnout Foot All EMG by 5.61 ms (Table 6.2 & Figure 6.2). On the other hand, Normal foot EMG latencies become shorter than Turnout foot from Shank EMG 4.97 ms lower but these are not significantly different. Between All EMG and Shank EMG, differences are 1.3 ms and 9.28 ms within Normal foot position and Turnout foot position respectively.

Table 6.2: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions

		Normal Foot	Turnout Foot	Sig.
All EMG	**Mean**	124.93	119.32	**0.034***
	SE	2.102	3.289	
Shank EMG	**Mean**	123.63	128.60	0.311
	SE	3.34	3.34	

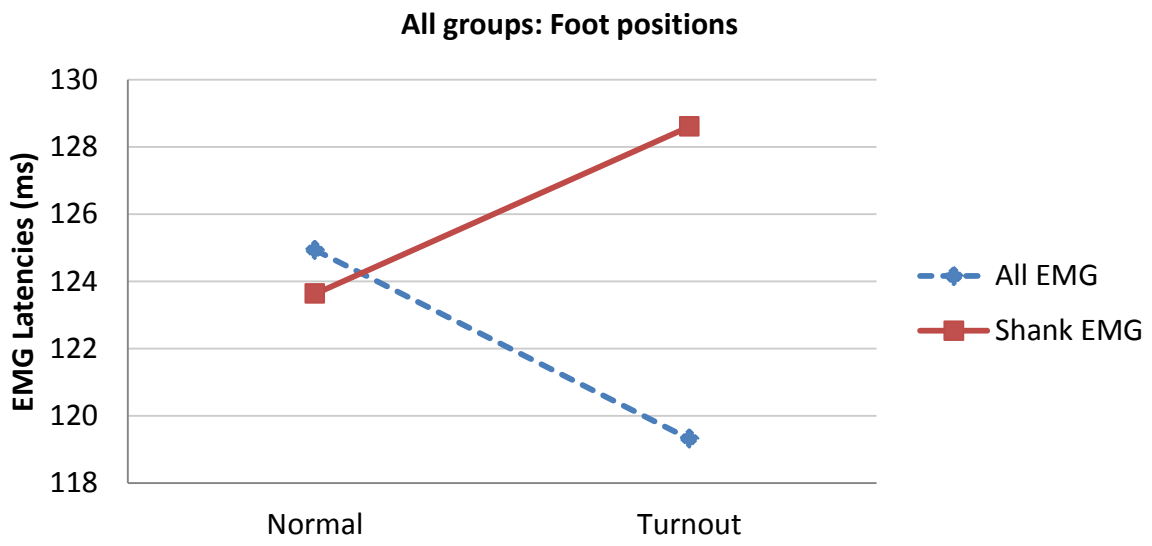


Figure 6.2: Mean graphs of the fastest All and Shank EMG latencies (ms) comparing with Normal foot and Turnout foot positions

The subjects may react quicker by using muscles on other parts of body than their lower legs when they are standing with Turnout foot position more than when in Normal foot position. Also, muscles on the Shank are possibly on a bit later with Turnout foot position than Normal foot position during single leg stance but this may not be considered as there is no significant value between Normal Shank EMG and Turnout Shank EMG.

6.1.3. Directions of Platform Movement

By comparing the fastest EMG latencies only within Directions of platform movement, graphs of both All EMG and Shank EMG have similar patterns, which Backward and Medial EMG latencies quicker than Forward and Lateral (Figure 6.3).

There are a significant differences between Forward and Medial directions from both All EMG (diff=6.31 ms & p=0.033) and Shank EMG (diff=7.23 ms & p=0.025) (Table 6.3). However, EMG latencies between Forward and Backward directions are not significantly different even though mean values of Backward is much quicker than Forward direction of platform movement (All EMG: diff=6.02 ms & p=0.153, Shank EMG: diff=8.13 ms & p=0.058).

As these comparisons do not differentiate Foot positions, it is difficult to determine causes of variations of EMG latencies based on the directions of platform movement.

Table 6.3: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors in four directions of platform movement

		Forward	Backward	Lateral	Medial
All EMG	**Mean**	125.30	119.28	124.93	118.99
	SE	3.461	2.926	3.792	2.864
	Sig.	B 0.153	F 0.153	F 0.899	F **0.033***
		L 0.899	L 0.124	B 0.124	B 0.941
		M **0.033***	M 0.941	M 0.161	L 0.161
Shank	**Mean**	130.87	122.74	127.22	123.64

EMG	**SE**	3.33		2.83		3.64		2.56	
	Sig.	B	0.058	F	0.058	F	0.271	F	**0.025***
		L	0.271	L	0.163	B	0.163	B	0.786
		M	**0.025***	M	0.786	M	0.319	L	0.319
Mean Diff All vs Shank		5.57		3.46		2.29		4.65	

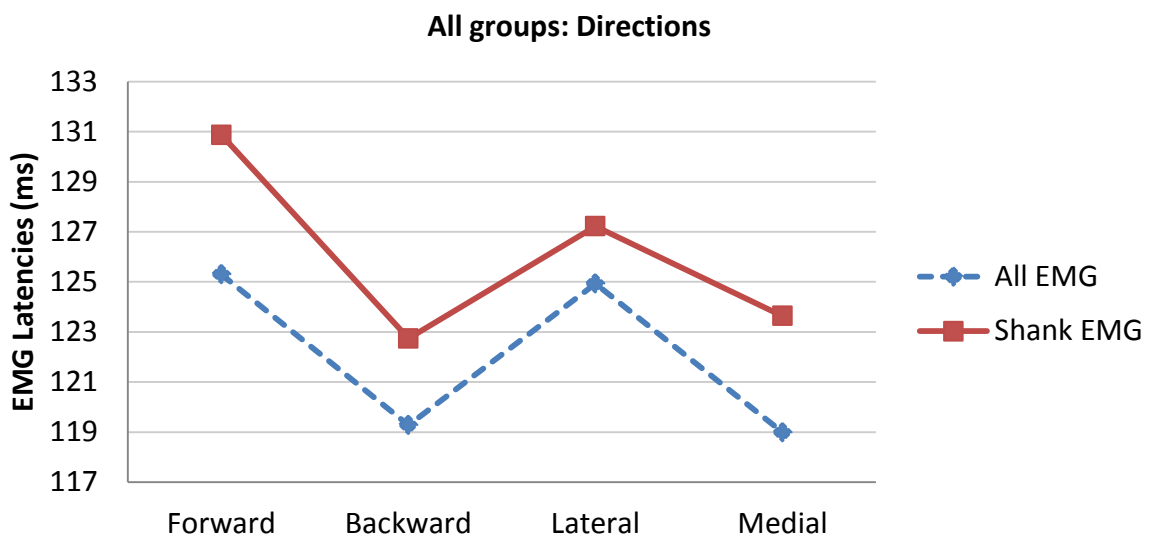


Figure 6.3: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on four directions of platform movement

6.1.4. Speeds

There was no significant difference amongst three speed options from both All EMG and Shank EMG latencies (Table 6.4 & Figure 6.4). The Slow mean values of EMG latencies are slightly longer than Fast but the speeds of platform movement do not seem to affect time of the fastest EMG latencies.

Table 6.4: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst Slow, Fast and combined Total speeds of platform

		Total (S + F)		Slow		Fast	
All EMG	**Mean**	122.11		122.62		121.64	
	SE	2.49		2.62		3.36	
	Sig.	Slow	0.769	Total	0.769	Total	0.785

		Fast	0.785	Fast	0.777	Slow	0.777
Shank EMG	**Mean**	126.11		127.02		125.23	
	SE	2.37		2.71		3.25	
	Sig.	Slow	0.627	Total	0.627	Total	0.640
		Fast	0.640	Fast	0.634	Slow	0.634

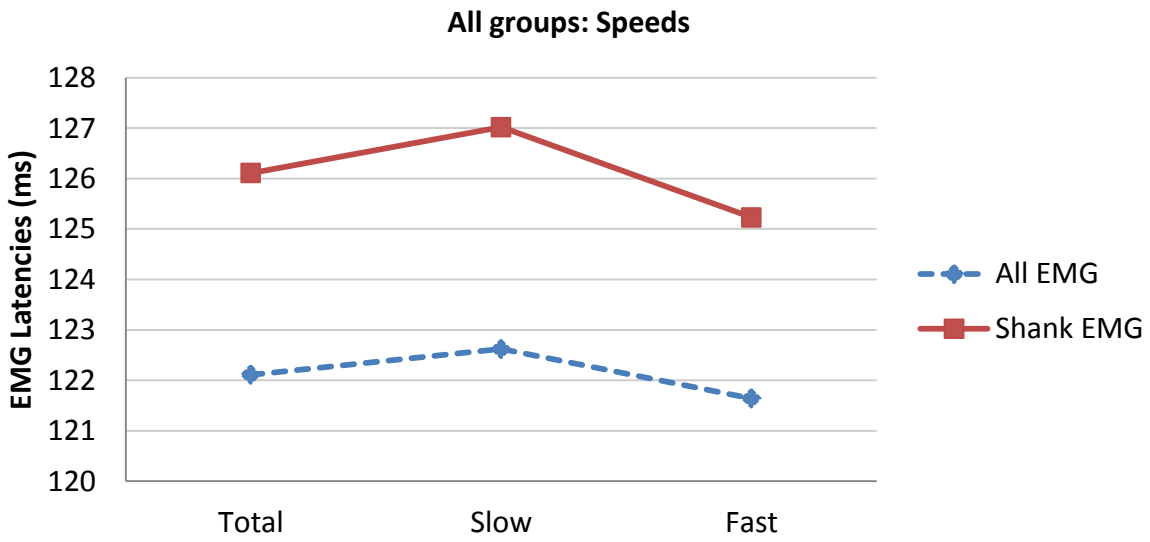


Figure 6.4: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on two speeds and Total (combined)

6.2. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on Dancer Group

A three-way Repeated Measures ANOVA was used to check significances in Foot positions, Directions of platform movement and Speeds of platform movement within the Dancer group.

6.2.1. Dancer Group: Foot Positions

There are no significant differences between Normal and Turnout foot positions from both All EMG and Shank EMG (All EMG: p=0.064 & Shank EMG: p=0.058). Turnout Foot EMG latency mean values are lower than Normal foot position (diff in All EMG=7.23 ms & diff in Shank EMG=9.18 ms). An assumption from the results could be that Dancers seem to react quicker after their balance is being perturbed in Turnout foot single leg stance than in Normal foot single leg stance.

Table 6.5: Mean and SE (Standard Error) values of EMG latencies (in ms) amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions based on Dancer group only

		Normal Foot	Turnout Foot	Sig.
All EMG	**Mean**	124.46	117.18	0.064
	SE	2.735	4.72	
Shank EMG	**Mean**	128.22	119.04	0.058
	SE	3.26	4.70	

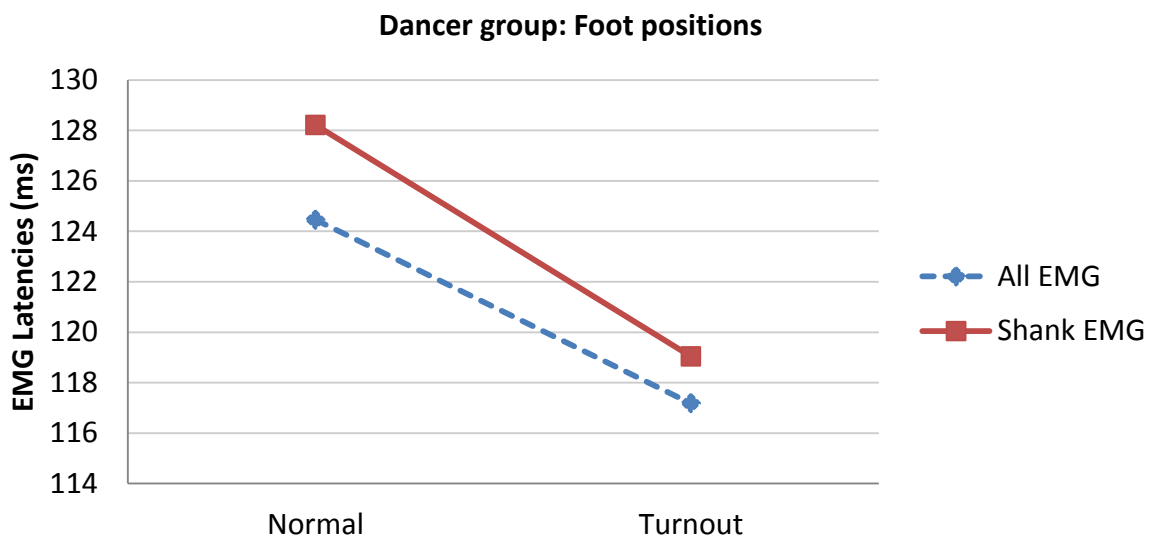


Figure 6.5: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Normal and Turnout foot positions from Dancer group

6.2.2. Dancer Group: Directions of Platform Movement

Non-significance is found amongst Directions of platform in Dancer group (Table 6.6). Nevertheless, Figure 6.6 shows a similar graph patterns with Figure 6.3 which includes comparisons of EMG latencies amongst Directions of platform movement from combined groups.

However, it is still hard to determine characteristic features of Dancers depending on Directions of platform movement as Foot positions are not checked separately in this statistical test.

Table 6.6: Mean and SE (Standard Error) values of EMG latencies amongst (in ms) all EMG sensors and three Shank EMG sensors in four directions of platform movement based on Dancer group only

		Forward		Backward		Lateral		Medial	
All EMG	**Mean**	123.34		118.93		121.70		118.31	
	SE	5.78		3.65		5.62		3.91	
	Sig.	B	0.465	F	0.465	F	0.555	F	0.117
		L	0.555	L	0.605	B	0.605	B	0.926
		M	0.117	M	0.926	M	0.577	L	0.577

Shank EMG	**Mean**	129.45		120.86		123.68		120.54	
	SE	5.77		3.90		5.58		3.53	
	Sig.	B	0.241	F	0.241	F	0.277	F	0.073
		L	0.277	L	0.570	B	0.570	B	0.957
		M	0.073	M	0.957	M	0.575	L	0.575
Mean Diff All vs Shank		6.11		1.93		1.98		2.23	

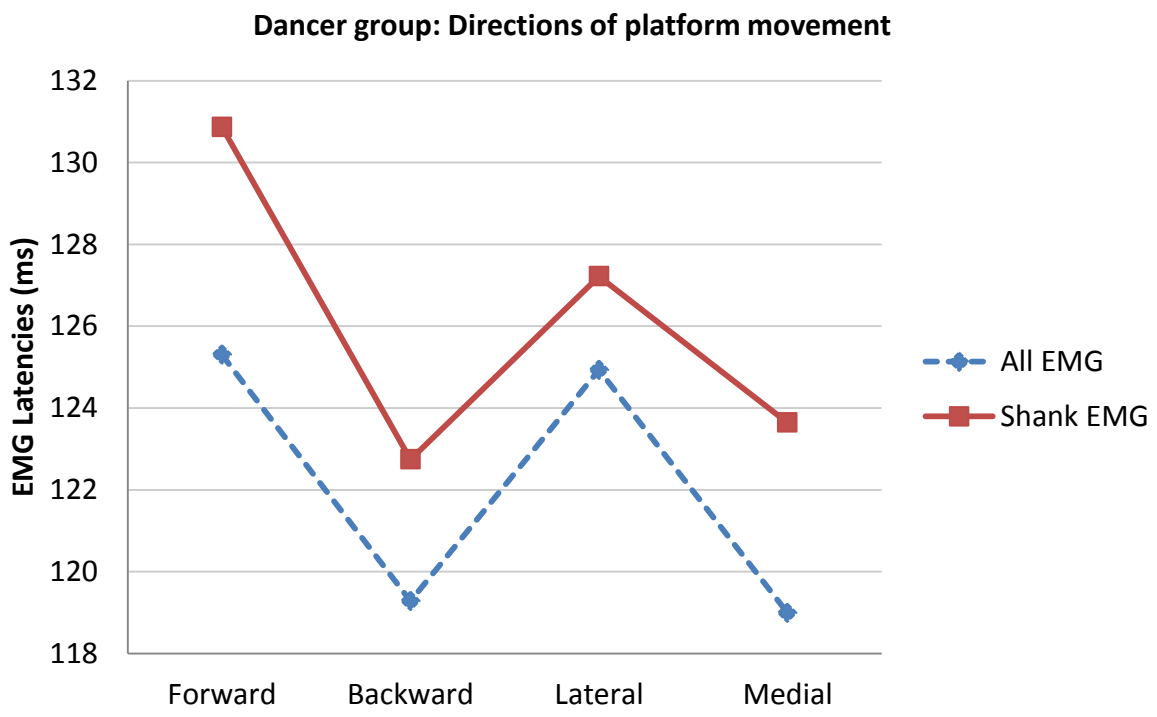


Figure 6.6: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Directions of platform movement from Dancer group

6.2.3. Dancer Group: Speeds of Platform Movement

The same as the result in 6.1.4 (Four-way Mixed ANOVA on Speeds, both groups are combined), there was no significant difference between Slow and Fast speeds. Also no significance is found between Total speed and All EMG or Shank EMG latencies (Table 6.7 & Figure 6.7).

Table 6.7: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors at Slow, Fast and combined Total speeds of platform based on Dancer group only

		Total (S + F)		Slow		Fast	
All EMG	**Mean**	120.80		119.55		122.12	
	SE	3.50		2.74		5.28	
	Sig.	Slow	0.611	Total	0.611	Total	0.594
		Fast	0.594	Fast	0.602	Slow	0.602
Shank EMG	**Mean**	123.61		122.37		124.92	
	SE	3.51		3.12		5.25	
	Sig.	Slow	0.639	Total	0.639	Total	0.622
		Fast	0.622	Fast	0.630	Slow	0.630
Mean Diff All vs Shank		2.81		2.82		2.8	

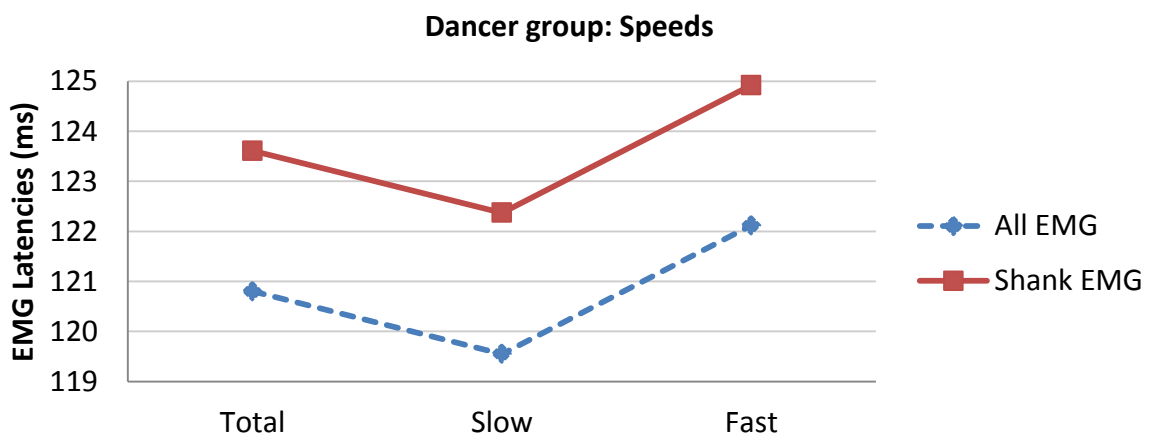


Figure 6.7: Mean graphs of the fastest All and Shank EMG latencies depending on Speeds from Dancer group

6.3. The Fastest EMG Latencies amongst All 11 and 3 Shank EMG Sensors Based on Gymnast Group

A three-way Repeated Measures ANOVA was applied to check significances in Foot positions, Directions of platform movement and Speeds of platform movement within the Gymnast group.

Overall, non-significances are found within comparisons of Foot positions, Directions of platform movement and Speeds of platform movement from Gymnast group. This might be caused by statistical limitation of Three-way Repeated Measures ANOVA because this analysis does not differentiate other independent variables during each comparison. Significances are found by using One-way Repeated ANOVA on Gymnast group at only Slow speed and findings are discussed in 6.5.3.

6.3.1. Gymnast Group: Foot Positions

There is no significant difference of the fastest EMG latencies between Normal and Turnout foot positions in Gymnast group from both All EMG and Shank EMG (Table 6.8 & Figure 6.8).

However, mean values of the fastest EMG latencies are shorter in Turnout foot position than in Normal foot position from both All EMG by 3.93 ms and Shank EMG by 2.91 ms. This pattern of result is the same as the result from Dancer group in 6.2.1 (Means EMG latencies of Turnout position is quicker). Therefore, it could be inferred that both Dancer and Gymnast groups have quicker reaction from one of the Shank muscles after the platform movement during Normal foot single leg stance than during Turnout foot single leg stance.

Table 6.8: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors between Normal and Turnout positions based on Gymnast group only

		Normal Foot	Turnout Foot	Sig.
All EMG	**Mean**	125.40	121.47	0.290
	SE	3.19	4.58	
Shank EMG	**Mean**	130.06	127.15	0.449
	SE	3.01	4.20	
Mean Diff All vs Shank		4.66	5.68	

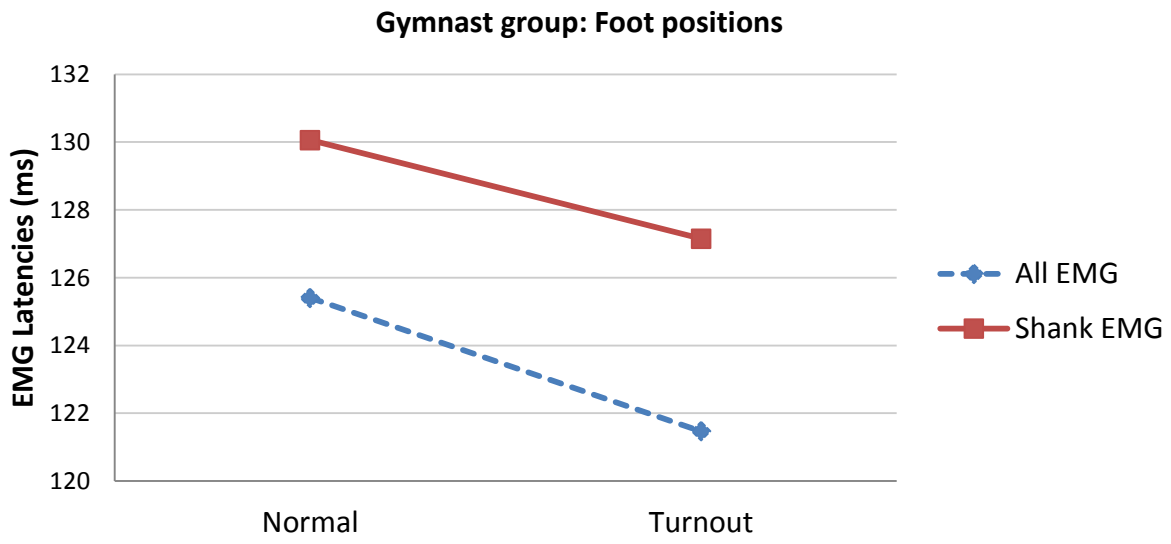


Figure 6.8: Mean graphs of the fastest All and Shank EMG latencies depending on Foot positions from Gymnast group

6.3.2. Gymnast Group: Directions of Platform Movement

There are no significant differences amongst Directions of platform movement (Table 6.9). However, mean values of both All EMG and Shank EMG have the similar shapes of graph (Figure 6.9) and these graphs look similar to the one from Dancer group (Figure 6.6). Overall, Forward and Lateral EMG latencies are longer than Backward and Medial EMG latencies but this is difficult to discuss from this statistical analysis as Foot positions are not separated out.

Table 6.9: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors in four directions of platform movement based on Gymnast group only

		Forward		Backward		Lateral		Medial	
All EMG	Mean	126.26		119.63		128.16		119.68	
	SE	3.81		4.58		5.09		4.19	
	Sig.	B	0.125	F	0.125	F	0.632	F	0.153
		L	0.632	L	0.108	B	0.108	B	0.992
		M	0.153	M	0.992	M	0.169	L	0.169
Shank EMG	Mean	132.30		124.61		130.80		126.75	
	SE	3.31		4.09		4.67		3.71	
	Sig.	B	0.107	F	0.107	F	0.718	F	0.202
		L	0.718	L	0.153	B	0.153	B	0.476
		M	0.202	M	0.476	M	0.393	L	0.393
Mean Diff All vs Shank		6.04		4.98		2.64		6.07	

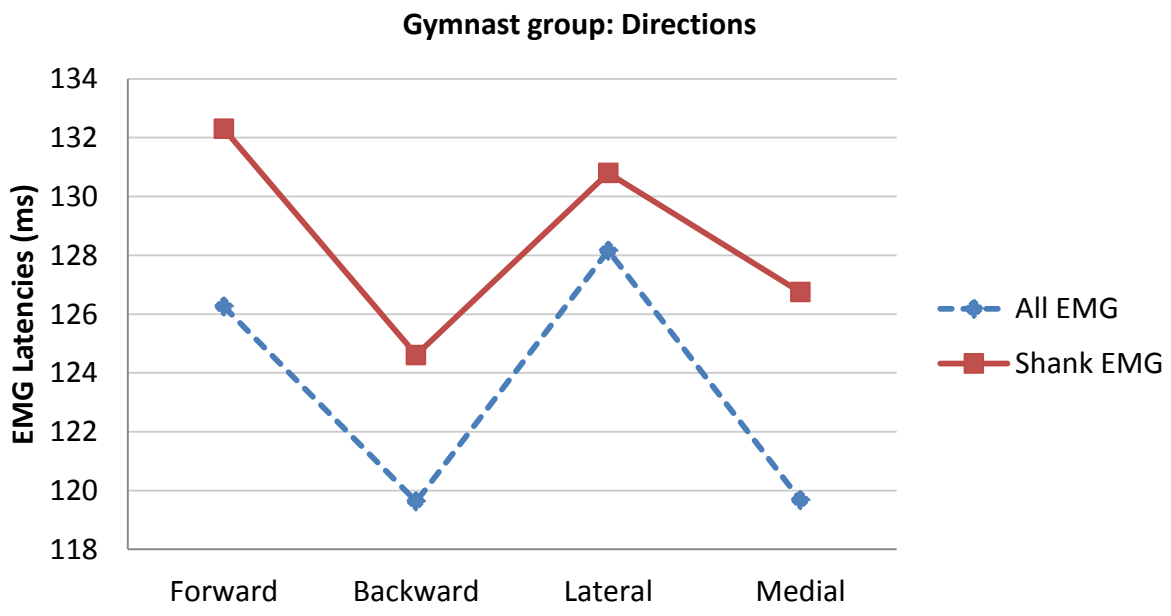


Figure 6.9: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Directions of platform movement

6.3.3. Gymnast Group: Speeds of Platform Movement

No significant difference is found between Slow and Fast speeds but Gymnasts seem to react quicker at Fast speed than at Slow speed. This result is opposite to the result from Dancers in 6.2.3 (Dancers probably react slower at Fast speed than at Slow speed). This difference between the groups might be related to their training methods or how the amount of perturbation affects their balance in Dance or Gymnastics that Dancers or Gymnasts have to handle to be in the range of their stable balance again. It is expected that Gymnasts probably have greater ranges of balance perturbation while they are doing Gymnastic movement (e.g. landing on the beam after a jump or somersault) than Dancers doing dance movement (e.g. standing on single leg with rising the other leg up and dancers are required to keep their balance stable as possible when they train).

Table 6.10: Mean and SE (Standard Error) values of EMG latencies amongst all EMG sensors and three Shank EMG sensors at Slow, Fast and combined Total speeds of platform based on Gymnast group only

		Total (S + F)		Slow		Fast	
All EMG	**Mean**	123.43		125.70		121.17	
	SE	3.55		4.46		4.14	
	Sig.	Slow	0.382	Total	0.382	Total	0.382
		Fast	0.382	Fast	0.382	Slow	0.382
Shank EMG	**Mean**	128.60		131.67		125.54	
	SE	3.17		4.43		3.81	
	Sig.	Slow	0.286	Total	0.286	Total	0.286
		Fast	0.286	Fast	0.286	Slow	0.286
Mean Diff All vs Shank		5.17		5.97		4.37	

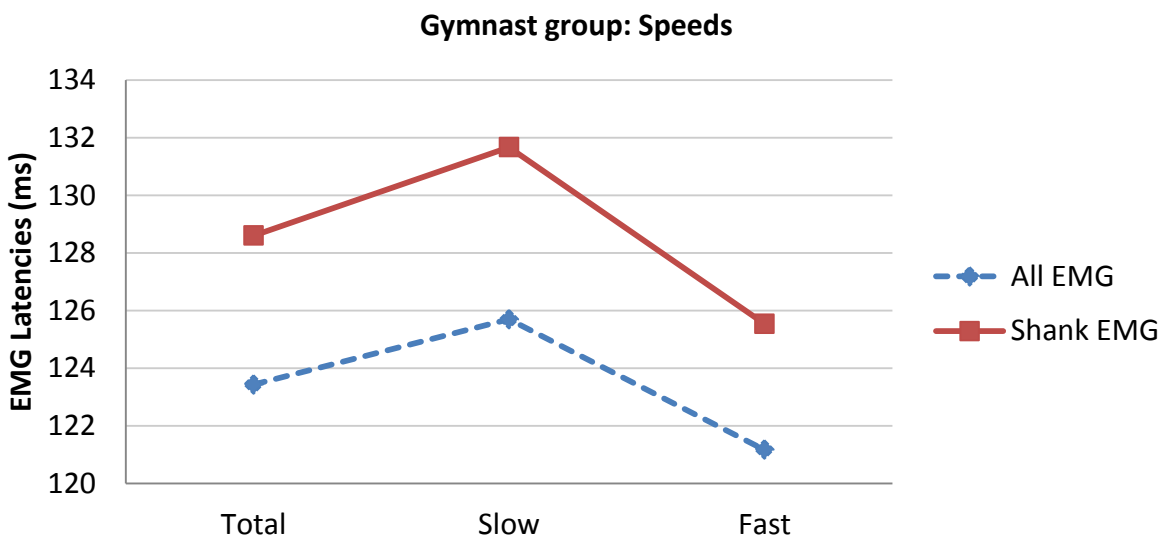


Figure 6.10: Mean graphs of the fastest All and Shank EMG latencies (ms) depending on Speeds

6.4. Comparisons of the Fastest EMG Latencies amongst 3 Shank EMG sensors between Dancer and Gymnast Groups (Independent samples T test)

Independent sample T test was used to compare the fastest EMG latencies amongst three Shank EMG sensors between Dancer group and Gymnast group at Slow and Fast speeds separately in each Foot position × each direction. The fastest Shank EMG latencies are significantly different between Dancer and Gymnast groups on Turnout foot single stance in Forward direction of platform movement at Slow speed (p=0.016) (Table 6.11 & Figure 6.11). The difference of mean is 30.33 ms and these results show that Dancers definitely react quicker than Gymnasts against Slow Forward directions of platform movement. However, for Fast Forward direction Dancers have quicker reaction than Gymnasts by 15.46 ms from Shank at Fast Forward platform movement with Turnout stance (Figure 6.12),however, the difference was not significant.

Dancers may be particularly strong to react fast when their body has started falling backward slowly (caused by Slow Forward platform movement) while they are standing on Turnout foot. Moreover, Dancers with Turnout position have quickest EMG latencies compared to Gymnasts and Normal position in all four directions at Slow speed. Therefore, it can be inferred that Dancers on Turnout foot single leg, possibly have good balance control after having a small amount of perturbation because they can react fast.

Table 6.11: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors with two foot positions in four directions at Slow, Fast speeds of platform movement (Independent samples T test was ran)

Foot positions	Directions	Speeds	Mean & SD (ms)	Dancer group	Gymnast group	Sig.
NORMAL	Forward	Slow	Mean	133.65	128.57	0.724
			SD	37.42	12.51	
		Fast	Mean	131.15	132.75	0.887
			SD	24.93	19.18	
	Backward	Slow	Mean	126.31	127.91	0.892
			SD	15.50	28.88	
		Fast	Mean	121.54	121.69	0.986
			SD	12.65	19.86	

	Lateral	**Slow**	Mean	127.84	145.23	0.123
			SD	10.65	26.88	
		Fast	Mean	126.57	124.70	0.833
			SD	26.74	23.38	
	Medial	**Slow**	Mean	128.63	140.74	0.312
			SD	16.27	28.29	
		Fast	Mean	130.25	118.90	0.307
			SD	24.13	18.33	
TURNOUT	**Forward**	**Slow**	Mean	111.01	141.34	**0.016***
			SD	18.75	25.21	
		Fast	Mean	141.99	126.53	0.296
			SD	35.89	18.25	
	Backward	**Slow**	Mean	113.38	117.91	0.661
			SD	23.83	15.84	
		Fast	Mean	122.40	130.93	0.477
			SD	23.33	23.46	
	Lateral	**Slow**	Mean	124.25	129.64	0.670
			SD	27.17	22.05	
		Fast	Mean	116.05	123.47	0.613
			SD	29.18	28.15	
	Medial	**Slow**	Mean	113.86	121.98	0.400
			SD	16.57	20.65	
		Fast	Mean	109.40	125.36	0.145
			SD	23.15	17.80	

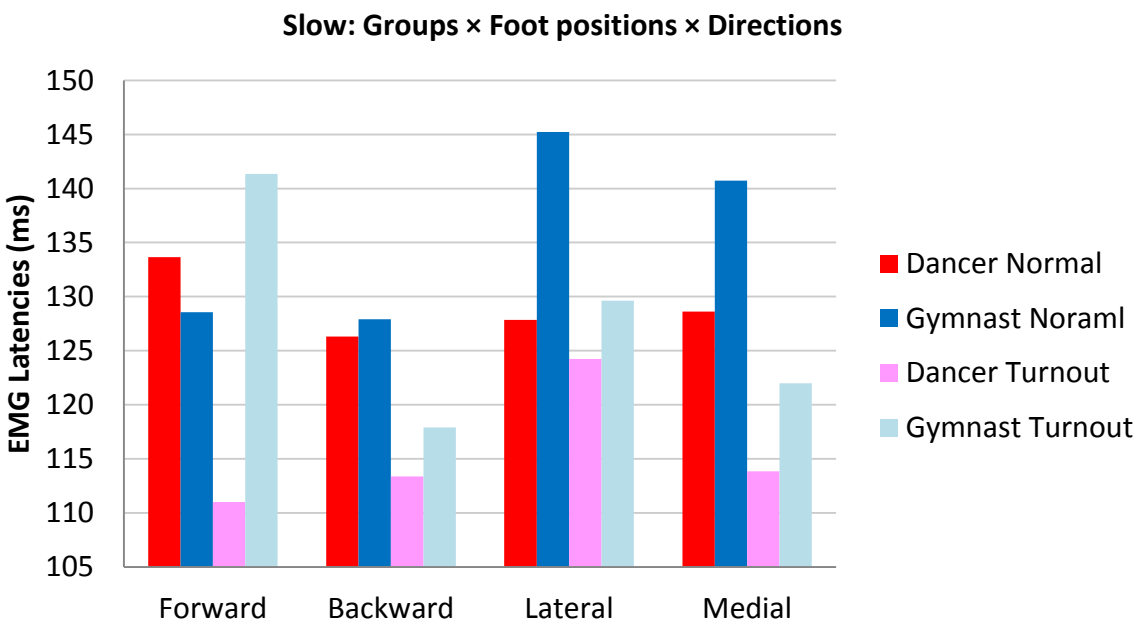


Figure 6.11: Mean graphs of the fastest Shank EMG latencies (ms) at Slow speed with plotting Groups and Foot positions together depending on Directions

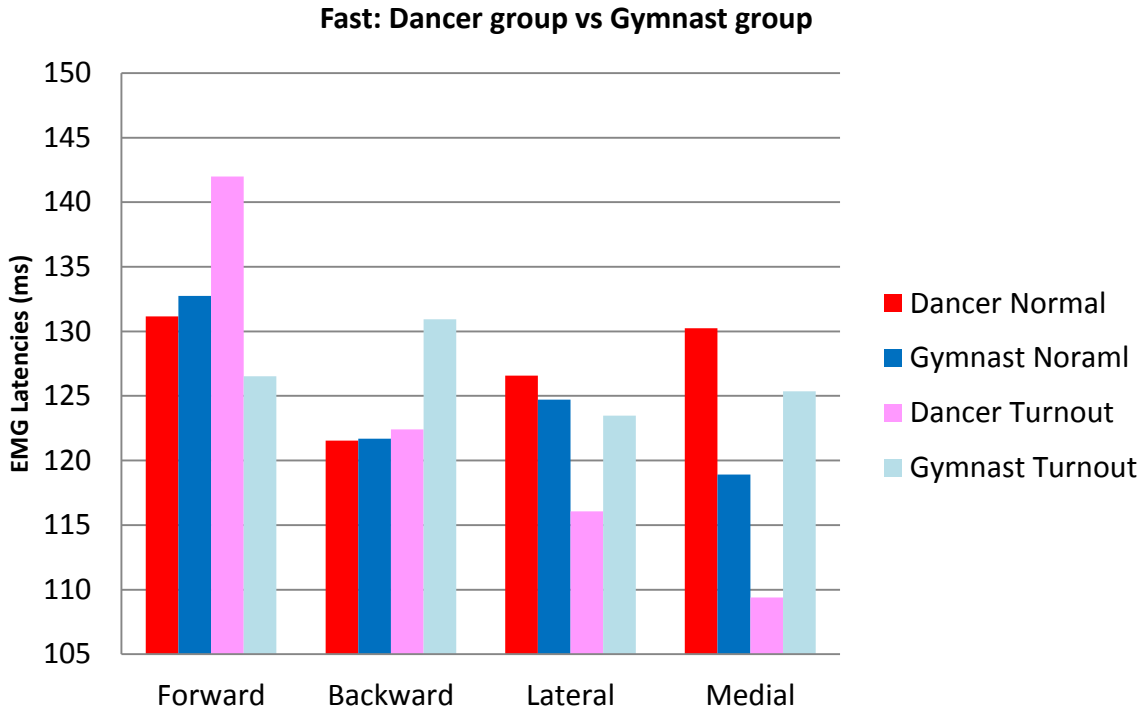


Figure 6.12: Mean graphs of the fastest Shank EMG latencies (ms) at Fast speed with plotting Groups and Foot positions depending on Directions

6.5. The Fastest EMG Latencies amongst 3 Shank EMG Sensors Comparing 'Foot positions × Directions' within the Same Speeds in the Separated Groups (One-way Repeated Measures ANOVA)

A one-way Repeated Measures ANOVA was used to compare the fastest Shank EMG latencies amongst Foot positions and Directions of platform movement within each group at each speed.

6.5.1. Dancer Group at Slow Speed: Foot positions × Directions

There is a significant difference between Normal foot Lateral movement (NL) and Turnout foot Forward movement (TF) at Slow speed of platform movement (p=0.032) (Table 6.12).

Table 6.12: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Dancer group with two foot positions in four directions at Slow speeds of platform movement

	Foot positions	Directions	Mean & SD	EMG Latencies		Sig.
Dancer Group at Slow	**Normal**	**Forward**	Mean	133.65	a	**0.032* (c & e)** 0.063 (c & h) 0.094 (d & e)
			SD	37.42		
		Backward	Mean	126.31	b	
			SD	15.50		
		Lateral	Mean	**127.84**	**c**	
			SD	10.65		
		Medial	Mean	128.63	d	
			SD	16.27		
	Turnout	**Forward**	Mean	**111.01**	**e**	
			SD	18.75		
		Backward	Mean	113.38	f	
			SD	23.83		
		Lateral	Mean	124.25	g	
			SD	27.17		
		Medial	Mean	113.86	h	
			SD	16.57		

These conditions have different first reacting muscles, which are Peroneus Longus (PL) and Tibialis Anterior (TA) from NL and TF, respectively in Chapter seven (7.1.2). This means these conditions are not causing relevant effects on balance as SD

values of both conditions are the smallest amongst directions within Foot positions. Dancers have more consistent length of EMG latencies in NL and TF at Slow speed.

Figure 6.13 shows the large difference of EMG latencies between Foot positions in Forward direction, between Normal Medial and Turnout Forward and Normal Lateral and Turnout Backward yet there was not significant differences between these conditions.

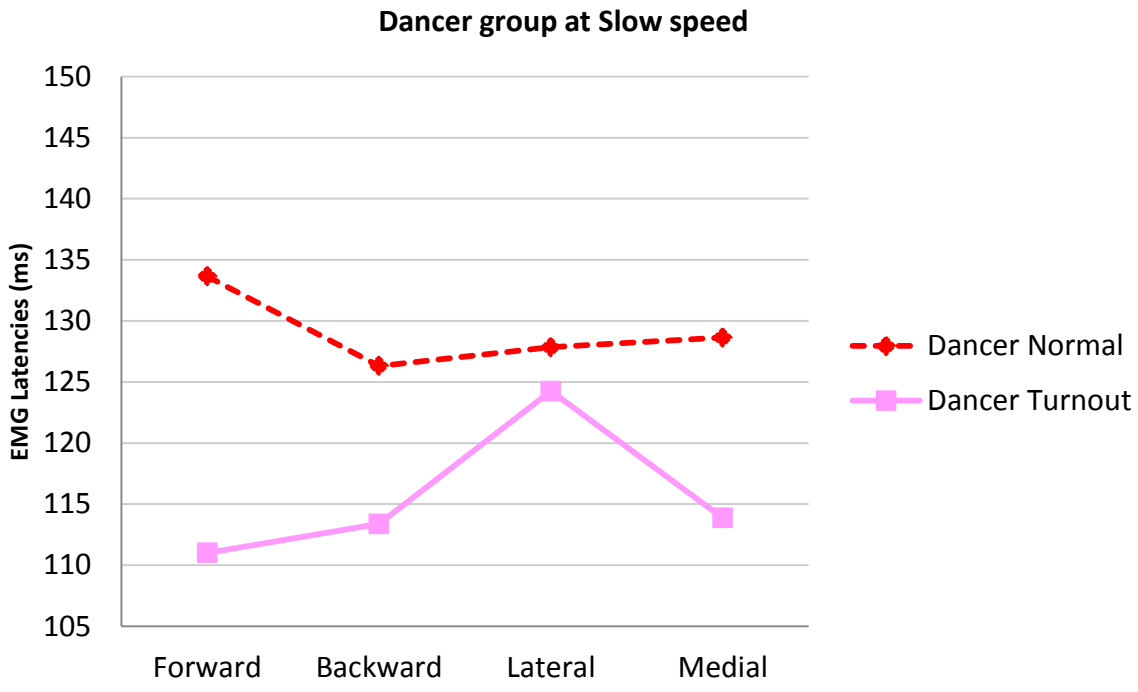


Figure 6.13: Mean graphs of the fastest Shank EMG latencies (ms) from Dancer group at Slow speed

6.5.2. Dancer Group at Fast Speed: Foot positions × Directions

There are significant differences in Normal Forward (NF) vs Turnout Medial (TM), Normal Medial (NM) vs TM, Turnout Forward (TF) vs Turnout Lateral (TL) and TF vs TM at Fast speed (Table 6.13).

Table 6.13: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Dancer group with two foot positions in four directions at Fast speeds of platform movement

	Foot positions	Directions	Mean & SD	EMG Latencies		Sig.
Dancer Group at Fast	**Normal**	**Forward**	Mean	**131.15**	**a**	**0.012* (a & h)** **0.026* (d & h)** **0.021* (e & g)** **0.039* (e & h)**
			SD	24.93		
		Backward	Mean	121.54	b	
			SD	12.65		
		Lateral	Mean	126.57	c	
			SD	26.74		
		Medial	Mean	**130.25**	**d**	
			SD	24.13		
	Turnout	**Forward**	Mean	**141.99**	**e**	
			SD	35.89		
		Backward	Mean	122.40	f	
			SD	23.33		
		Lateral	Mean	**116.05**	**g**	
			SD	29.18		
		Medial	Mean	**109.40**	**h**	
			SD	23.15		

The most interesting finding is that the Foot positions affect EMG latencies in Medial direction of platform movement (NM vs TM). The first reaction muscle is TA from both NM and TA conditions at Fast speed in Chapter seven (7.1.2) but mean value of TM latency is shorter than NM (20.85 ms). Therefore, the difficulty of the perturbation (combined Foot positions and Directions) might influence EMG latencies of Shank muscles (NM is probably harder to keep balance than TM). The similar inference would be probably applied to the significantly different comparison between NF and TM as the firstly reacted muscle is TA from NF condition.

Within Turnout positions, TF is significantly different against TL and TM and TF has the longest Mean value of EMG latency compared to others. Another interesting

finding is that EMG latencies of both Foot positions are similar in Backward direction of platform movement.

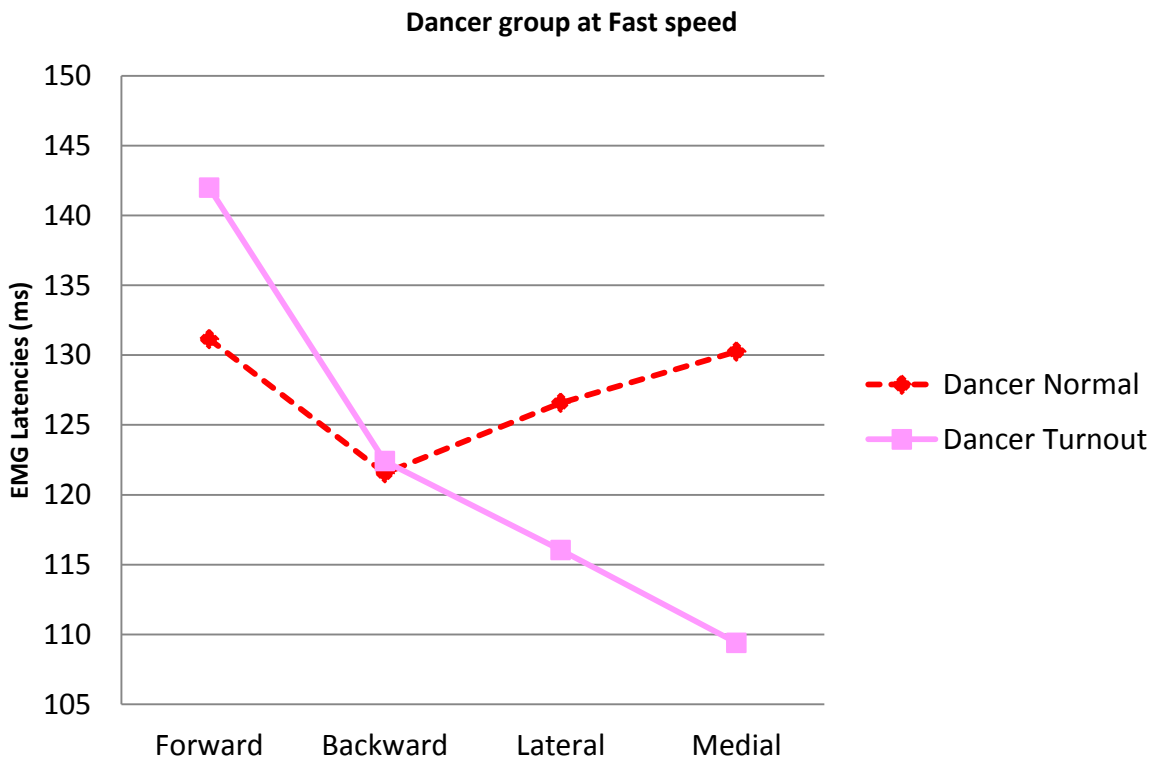


Figure 6.14: Mean graphs of the fastest Shank EMG latencies (ms) from Dancer group at Fast speed

6.5.3. Gymnast Group at Slow Speed: Foot positions × Directions

Comparisons in NL vs TB (p=0.021) and in TF vs TB (p=0.041) have significant differences (Table 6.14). PL is the 1st reaction muscle in both NL and TB from Chapter seven (in 7.1.3) and the mean difference is 27.32 ms which is the longest difference between latencies compared to other comparisons. Therefore, Gymnasts can react quicker by using PL after having TB than NL and TB is probably easier to keep balance than NL at Slow speed for Gymnasts.

Within Turnout position, the mean EMG latency of TF is longer than TB's mean value (23.43 ms) and the first reaction muscle among Shank EMG sensors is TA muscle for TF condition (Figure 6.15). This may mean that Slow Forward platform

movement is probably harder to react fast than Slow Backward for Gymnasts during Turnout single leg stance.

Table 6.14: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Gymnast group with two foot positions in four directions at Slow speeds of platform movement (One-way Repeated measures ANOVA was ran)

	Foot positions	Directions	Mean & SD	EMG Latencies		Sig.
Gymnast Group at Slow	**Normal**	**Forward**	Mean	128.57	a	**0.021* (c & f)** **0.041* (e & f)** 0.089 (b & e)
			SD	12.51		
		Backward	Mean	127.91	b	
			SD	28.88		
		Lateral	Mean	**145.23**	**c**	
			SD	26.88		
		Medial	Mean	140.74	d	
			SD	28.29		
	Turnout	**Forward**	Mean	**141.34**	**e**	
			SD	25.21		
		Backward	Mean	**117.91**	**f**	
			SD	15.84		
		Lateral	Mean	129.64	g	
			SD	22.05		
		Medial	Mean	121.98	h	
			SD	20.65		

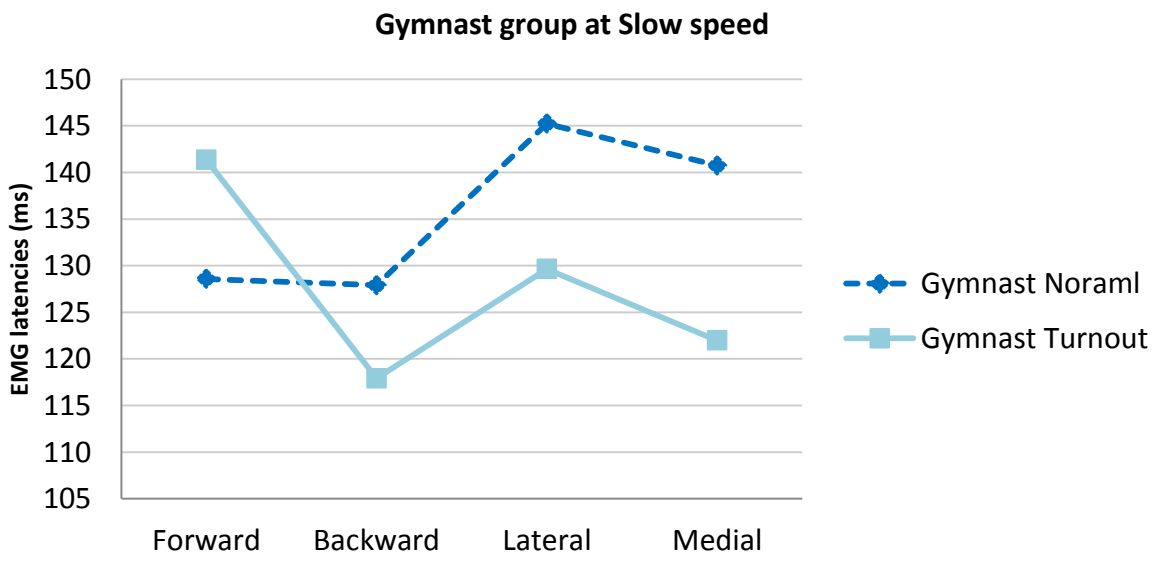


Figure 6.15: Mean graphs of the fastest Shank EMG latencies (ms) from Gymnast group at Slow speed

6.5.4. Gymnast Group at Fast Speed: Foot positions × Directions

Non-significance is found from comparisons across Foot positions and Directions of platform movement at Fast speed in the Gymnast group (Table 6.15). It is because mean values are not too different among each condition (Figure 6.16) and it can be considered that Gymnasts' EMG latencies at Fast platform movement become more consistent than at Slow.

Table 6.15: Mean and SD (Standard Deviation) values of EMG latencies amongst three Shank EMG sensors from Gymnast group with two foot positions in four directions at Fast speeds of platform movement (One-way Repeated measures ANOVA was ran)

	Foot positions	Directions	Mean & SD	EMG Latencies		Sig.
Gymnast Group at Fast	Normal	Forward	Mean	132.75	a	No Significance
			SD	19.18		
		Backward	Mean	121.69	b	
			SD	19.86		
		Lateral	Mean	124.70	c	
			SD	23.38		
		Medial	Mean	118.90	d	
			SD	18.33		
	Turnout	Forward	Mean	126.53	e	
			SD	18.25		
		Backward	Mean	130.93	f	
			SD	23.46		
		Lateral	Mean	123.47	g	
			SD	28.15		
		Medial	Mean	125.36	h	
			SD	17.80		

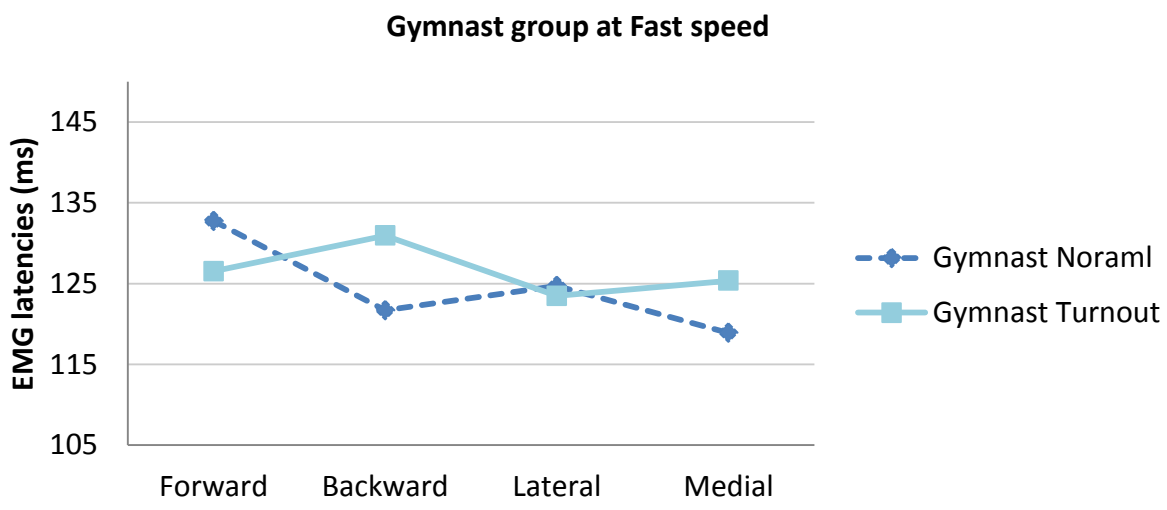


Figure 6.16: Mean graphs of the fastest Shank EMG latencies (ms) from Gymnast group at Fast speed

6.6. Discussions

The related research questions are:

- Q3. Are balance strategies related to dance positions (Turnout versus Normal) and/or level of difficulty (Flat feet versus Demi-Pointe)?

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

Turnout position might be an ideal stance to prevent falls during sports or exercise which are challenging for balance. EMG latencies from the 3rd study show that Turnout foot position is generally quicker than Normal foot position from both Dancers and Gymnasts. Dancers can react much quicker to overall perturbations in Turnout foot than Gymnasts and compared to standing in Normal foot position. Dancers are particularly good to react quickly in Turnout foot at Slow Forward platform movement (quicker EMG latencies) compared to Gymnasts. Turnout foot position on single leg may be helpful to react at various directions of falls because of way of increasing the BOS (wider in ML direction than Normal foot). Also, having good balance reaction skills performed via muscles can be due to training or adaptation that Dancers have practised as these may have affected motor tone (Judge, 2003).

Dancers seem to react quicker than Gymnasts and Dancers might be better at Slow perturbation than at Fast compared to Gymnasts as dancers are trained in small balance perturbation, for example, ‘adagio’ which is slow movement in ballet and dancers stand on single leg and rise & bring down the other leg slowly in various direction. Oppositely, Gymnasts might react quicker at Fast perturbation than Slow. According to Johnson & Woollacott (2011), training methods may develop athletes’

balance control during recovery after having balance perturbations. In their research, power-trained athletes had quicker EMG onsets and larger ankle muscle contraction especially at Fast speed of perturbation (10 cm at 80 cm/s) compared to endurance-trained athletes. Therefore, it is emphasised that high resistance muscle strength training may help humans to solve balance problems and to control their balance more effectively when they face falling.

Some researchers have explained how dancers rely on somatosensory proprioception and vision during balance. There are two different opinions that 'vision is not really important for dancers' vs 'vision affects balance performance of dancers'. Simmons (2005a) reported that visual information (only visual information is being disturbed) may not affect dancers' balance but a lack of somatosensory proprioceptive information may change balance so it is less stable for dancers. Therefore, dancers' balance control seems to rely on somatosensory proprioceptive system more than visual information.

Golomer et al. (1999)'s research reported that postural control and perception of dancers were more stable and independent from visual inputs while vision was covered (eyes-closed) compared to non-dancers. This research emphasised that elite performers (especially dancers) may have transferred their sensorimotor dominance from vision to proprioception which is enhanced by long periods of training. Moreover, Asseman & Gahery (2005) also reported similar findings that vision may not contribute as much as other sensory inputs to gymnasts' handstand. Vuillerme et al. (2001) found that both gymnast and non-gymnast groups increased their postural sway on single leg balance and double legs balance when their vision was removed but the effect of removed vision was less obvious on gymnasts. Vuillerme et al.'s research asserted that gymnasts have abilities to compensate for the lack of vision with other sensory systems (e.g. somatosensory proprioceptive system) and/or there may be more developed sensory systems overall in gymnasts compared with other populations. Therefore, good balance performers (e.g. dancers and gymnasts) may have good balance or/and coordination skills due to their well-trained & developed somatosensory proprioceptive system that makes them less dependent on visual information (they need less visual information) (Goldmer et al., 1999).

On the other hand, some researches pointed out the importance of vision on dancers. Perrin et al. (2002) found that both judoists and dancers performed better balance control than normal populations (a control group) with eyes-opened. However, only judoists were superior at balance control during the eyes-closed condition compared to dancers and controls. Therefore, visual information may be important to regulate better balance for dancers, which is due to dancers' training (a very stable environment, e.g. looking at a mirror and holding a bar). Oppositely, training of judoists would focus on somatosensory feedback to maintain their balance stable in various situations. Gautier et al. (2007) mentioned that using vision can be an important role for gymnasts during handstand as more variations of COP appeared during eye-closed handstand even if gymnasts could manage to balance. Hutt (2015) suggested that balance control of ballet dancers can be improved by training in eyes-closed condition. This may shift dependency of visual information to use more proprioceptive information and even possibly help reducing risks to have injuries.

Compared to standing on double legs, EMG latencies seem to be longer and it might be because single leg stance is harder to balance than double legs stance. CNS may have been sending and receiving more information to control balance on single leg compared to normal situation standing (humans normally stand on double legs, even if for dancers, they would spend more time on double legs than on single). Therefore, humans might have difficulties to react quickly enough at sudden balance perturbation when they are already balancing on single leg compared to standing normal on double legs.

Answering research questions across studies of this thesis is discussed in Chapter 8 &10.

CHAPTER 7

Non-parametric and Frequency order Tests on EMG Latencies from 3 Shank Muscles on Single Leg Balance in Dynamic Conditions

This chapter is shown the results and discussions of Non-parametric and frequency order tests from the 3rd study and this study: Single leg balance in dynamic conditions. More information of these tests is shown in the end of Chapter 3.

This Chapter 7 is linked to research question Three, Five and Six:

- Q3. Are balance strategies related to dance positions (Turnout versus Normal) and/or level of difficulty (Flat feet versus Demi-Pointe)?

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

7.1. All Groups between Foot Positions

7.1.1. All Groups in Normal Foot Position

The 1st reacting muscles with normal foot positions are Tibialis Anterior (TA) from the Forward platform movement, Gastrocnemius (GA) in the Backward platform movement, Peroneus Longus (PL) in Lateral platform movement and TA in the Medial platform movement as highlighted in red in Table 7.1. These results are the same for slow and fast perturbations in each direction.

The percentages when the 1st reacting muscle was the first reacting ($\%_A$) that PL acts first more frequently in the Lateral direction of platform movement than other muscles with their related directions. Comparing the percentages of the first reacting

muscles between two speeds of platform movements, the percentages from Fast are generally larger than the ones from Slow, apart from Lateral direction (Slow: 75.00% > Fast: 72.92%). The Lateral direction has the same orders from both Non-parametric and from frequency order test (PL - TA - GA) at all conditions of speed.

In $\%_B$ of total speeds (not differentiating speeds), the percentages of 3rd reacting muscles are higher than the 1st muscles in the Backward and Medial directions (Backward: TA [3rd] > GA [1st], Medial: PL [3rd] > TA [1st]) but not in the Forward and Lateral directions. This shows that TA and PL are less working in the Backward and Medial directions respectively and these are probably not the main muscles to maintain balance at the beginning of falling in each direction (Backward platform movement: occurring falling forward, Medial platform movement: probably starting falling lateral first).

However, the 3rd reacting muscle $\%_B$ from Forward Fast (GA: 73.91%) gets higher than the percentage of 1st reacting muscle (TA: 64.58%) compared to the ones from total and slow. This may be caused because the fast platform movement helps the muscles to work more consistently compared to the slow movement in the Forward direction with normal foot position.

Table 7.1: Non-parametric and frequency order test from Normal Foot Position of All groups

All groups - Normal Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	1	2	3	3	2	1	2	1	3	1	3	2
	FO		=			=			=			=	
	$\%_A$	63.54	28.26	9.47	11.83	29.79	59.57	18.95	73.96	7.45	59.38	8.97	33.33
	$\%_B$	63.54	39.13	60.00	68.82	50.00	59.57	47.37	73.96	59.57	59.38	71.79	47.92
Slow	NP	1	2	**3**	3	2	1	2	1	3	1	3	2
	FO	1		**2, 3**		=			=			=	
	$\%_A$	62.50	23.91	14.58	11.11	39.13	52.17	17.02	75.00	8.51	50.00	17.65	37.50
	$\%_B$	62.50		37.50	66.67	41.30	52.17	55.32	75.00	63.83	50.00	61.76	43.75

				47.92									
Fast	NP	1	2	3	3	2	1	2	1	3	1	3	2
	FO		=			=			=			=	
	$\%_A$	64.58	32.61	4.35	12.50	20.83	66.67	20.83	72.92	6.38	68.75	2.27	29.17
	$\%_B$	64.58	45.65	73.91	70.83	58.33	66.67	39.58	72.92	55.32	68.75	79.55	52.08

(NP: Non-parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

7.1.2. All Groups in Turnout Position

TA (73.96%) in Forward, PL (51.04%) in Backward, PL (59.38%) in Lateral and TA (48.42%) & GA (48.96%) in Medial react first with turnout foot position based on total speed results ('Forward: TA' > 'Lateral: PL' > 'Backward: PL' > 'Medial: TA&GA') (Table 7.2).

Table 7.2: Non-parametric and frequency order test from Turnout Foot Position of All groups

All groups - Turnout Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	1	3	2	3	1	2	2	1	3	**1**	3	**2**
	FO	1	2	3		=			=		**2**	3	**1**
	$\%_A$	73.96	15.29	11.96	13.98	51.04	35.42	33.68	59.38	8.05	48.42	5.00	48.96
	$\%_B$	73.96	45.88	47.83	67.74	51.04	47.92	41.05	59.38	66.67	43.16	78.75	48.96
Slow	NP	1	**3**	**2**	3	1	**2**	2	1	3	1	3	2
	FO	1	**2**	**2, 3**	3	1	**1, 2**		=			=	
	$\%_A$	66.67	17.07	17.78	21.74	39.58	39.58	31.91	60.42	8.89	55.32	2.78	43.75
	$\%_B$	66.67	43.90	40.00 42.22	65.22	39.58	39.58 50.00	36.17	60.42	57.78	55.32	86.11	45.83
Fast	NP	1	**2**	**3**	3	1	2	2	1	3	**2**	3	**1**
	FO	1	2	3		=			=			=	
	$\%_A$	81.25	13.64	6.38	6.38	62.50	31.25	35.42	58.33	7.14	41.67	6.82	54.17
	$\%_B$	81.25	47.73	53.19	70.21	62.50	45.83	45.83	58.33	76.19	41.67	72.73	54.17

(NP: Non-parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

Interestingly, non-parametric (TA - GA - PL) and frequency order (GA - TA - PL) tests show different orders in the orders of the 1st and 2nd reaction muscles. Comparing $\%_A$ between TA and GA in the Medial direction Total based on frequency order test, GA is slightly higher than TA (diff: 0.54%). In the Medial direction of platform movement with slow speed TA works first in both non-parametric and frequency order test (55.32%) but GA is the first reaction muscle in the Medial direction at Fast from both non-parametric and frequency order (54.17%) tests. Therefore, there are more possibilities to have TA reacts the first at slow platform movement and GA may react first more often at the fast speed in the Medial direction of platform movement.

In the Forward direction, non-parametric test order at Fast platform movement shows swapped orders between the 2nd and 3rd reacting muscles compared to Forward Total (Total: TA - GA - PL, Fast: TA - PL - GA, highlighted in blue) which means PL probably had to be worked secondly to keep balance after falling backward fast which was caused by the Fast Forward platform movement. TA works mostly first in the Forward direction, especially with the Fast translation (81.25%).
At the Slow platform movement, the results of frequency order GA have more than one rank in Forward (2nd & 3rd) and Backward (1st &2nd) directions. These are possibly caused because turnout foot position might have more variations to control balance in Slow Forward and Backward directions. GA in Forward, TA in Backward, GA in Lateral and PL in Medial are the slowest reacting muscles in turnout foot position

7.1.3. All Groups Comparing Normal and Turnout Positions

Table 7.1 and 7.2 show that the first reacting muscle can be differed due to the different foot positions even if the platform moves in the same direction. TA is normally on first in the Forward platform movement with both normal and turnout foot positions and this muscle looks more consistently working first with turnout foot position than normal foot position in the Forward direction. Also, there seems to be more variations between the 2nd and 3rd reacting muscles with turnout position than Normal position depending on the speeds and non-parametric & Frequency order tests.

In the Backward direction, the firstly reacted muscles are different with two foot positions (GA: Normal foot, PL: Turnout foot). Generally, PL and TA work sequentially subsequent to the 1st reacting muscle with normal foot position (GA - PL - TA) and GA and TA react later with turnout foot position (PL - GA - TA).

In the Lateral platform movement, results from both normal and turnout foot positions have the same orders of muscle reactions in which PL works first and then TA and GA react sequentially. This means PL is important in the Lateral direction with both foot positions and this muscle works first with turnout foot, but less than with normal foot, because turnout foot was not perfectly 90° turnout. It is expected that if the foot position is the more turnout, TA may contribute the more as the 1st reacting muscle to the Lateral direction by comparing the percentages of frequency orders between TA and PL depending on foot positions (‘Normal - TA: 39.58%, PL: 72.92%’ VS ‘Turnout - TA: 45.83%, PL: 58.33%’).

Lastly, TA reacts first and TA & GA work first in the Medial direction with normal and turnout foot positions respectively. Normal foot has the constant order of TA, GA and PL but the results of turnout foot show more variations compared to the result of normal foot position (‘TA [1st] - GA [2nd] - PL [3rd]’ or ‘GA [1st] - TA [2nd] - PL [3rd]’). An important thing here can be PL is not the major muscle to react first in the Medial direction with both normal and turnout positions.

7.2. Dancer Group between Foot Positions

7.2.1. Dancer Group in Normal Foot Position

In Dancer group, the orders between non-parametric and Frequency order tests were the same in each direction at each speed with Normal foot position. TA (Total: 66.67%) in Forward, GA (Total: 53.19%) in Backward, PL (Total: 72.92%) in Lateral, and TA (Total: 58.33%) in Medial are the 1st reacting muscles ($\%_A$). This result is the same with Normal foot position of all groups previously mentioned ('Lateral: PL' > 'Forward: TA' > 'Medial: TA' > 'Backward: GA') (Table 7.3).

Moreover, the sequential orders in each direction show the same results too as the orders of All groups' Normal foot position (Forward: TA - PL - GA, Backward: GA - PL - TA, Lateral: PL - TA - GA, Medial: TA - GA - PL) apart from the order of Slow Forward platform movement (TA - GA - PL).

Table 7.3: non-parametric and Frequency order test from Normal Foot Position of Dancer group

Dancer group - Normal Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	1	2	3	3	2	1	2	1	3	1	3	2
	FO		=			=			=			=	
	$\%_A$	66.67	22.22	12.77	17.02	29.79	53.19	17.02	72.92	10.64	58.33	10.53	33.33
	$\%_B$	66.67	46.67	61.70	68.09	53.19	53.19	46.81	72.92	61.70	58.33	76.32	52.08
Slow	NP	1	3	2	3	2	1	2	1	3	1	3	2
	FO		=			=			=			=	
	$\%_A$	58.33	27.27	16.67	13.04	34.78	52.17	13.04	75.00	13.04	50.00	18.75	37.50
	$\%_B$	58.33	50.00	41.67	60.87	39.13	52.17	52.17	75.00	60.87	50.00	68.75	50.00
Fast	NP	1	2	3	3	2	1	2	1	3	1	3	2
	FO		=			=			=			=	
	$\%_A$	75.00	17.39	8.70	20.83	25.00	54.17	20.83	70.83	8.33	66.67	4.55	29.17

$\%_B$	75.00	69.57	82.61	75.00	66.67	54.17	41.67	70.83	62.50	66.67	81.82	54.17

(NP: Non-parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

Comparing $\%_B$ amongst Total, Slow and Fast speeds, Slow speed has lower percentages in each order than Total and Fast in the Forward direction (highlighted in blue in Table 7.3). The slow movement might allow the muscles to work less consistently which means Tibialis does not need to be always on first and other muscles can support balance because Slow Forward movement may be easy for dancers to maintain their balance. This can be the reason why only Slow speed has different sequential orders compared against other speeds in Forward direction with Normal foot position.

Between Slow and Fast movements, it can be seen that Fast movement may help muscles to work consistently in their orders in the Forward, Backward and Medial directions by comparing the percentages of frequency orders. Fast platform movement seems to perturb dancers' balance more than with Slow movement in Lateral direction (1st: 75.00% (SL) > 70.83% (FL), 2nd: 52.17% (SL) > 41.67% (FL)).

7.2.2. Dancer Group in Turnout Foot Position

Based on non-parametric test, the 1st reacting muscles in Turnout foot position from Dancer group are the same with the results from all groups in Turnout position apart from in the Medial direction (TA in Medial direction from All group) (Table 7.4).

In the Medial direction, the order of Total (combined results from Slow and Fast speeds) from non-parametric test is GA, TA and PL (but, from All groups: TA [1st] - GA [2nd] - PL [3rd]) which is different to Frequency order test from Total (GA [1st] - GA [2nd] - PL [3rd]). TA and GA react first mainly in Medial direction with Turnout foot from Dancer group the same as All groups. From considering only non-parametric and frequency order tests, GA seems to react slightly more than TA in Medial direction with Turnout foot.

However, TA may help more dancers during the Fast Medial platform movement than during Slow movement (Slow: TA [2nd], Fast: TA [1st]). PL react definitely the latest after Medial platform movement because this has the highest percentages to be the 3rd reacting muscle. Also, these numbers of percentages are a lot higher than any other percentages across the directions and speeds ($\%_B$ - Total: 90.00%, Slow: 100.00%, Fast: 82.61%). By comparing these percentages of the 3rd reacting muscle from Frequency Order test on PL, this muscle needs to react earlier than be the 3rd only during the Fast movement (probably as 2nd reacting muscle) even if this muscle is used only as the 3rd reacting 100 % during Slow movement.

Findings in other directions are similar to the ones from All groups which are mentioned in 7.1.2.

Table 7.4: non-parametric and Frequency order test from Turnout Foot Position of Dancer group

Dancer Group - Turnout Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	1	2	3	3	1	2	2	1	3	2	3	**1**
	FO		=			=			=			3	**1, 2**
	$\%_A$	75.00	16.28	8.70	16.67	47.92	35.42	29.79	64.58	6.67	47.92	2.50	50.00
	$\%_B$	75.00	48.84	54.35	62.50	47.92	45.83	44.68	64.58	68.89		90.00	50.00 47.92
Slow	NP	1	**3**	**2**	3	1	**2**	2	1	3	2	3	1
	FO	1		**2, 3**	3	1	**1, 2**		=			=	
	$\%_A$	70.83	19.05	9.09	25.00	37.50	37.50	26.09	70.83	4.35	45.83	0.00	54.17
	$\%_B$	70.83	42.86	40.91 50.00	58.33	37.50	37.50 50.00	43.48	70.83	60.87	54.17	100.0	54.17
Fast	NP	1	2	3	3	1	2	2	1	3	**1**	**3**	**2**
	FO		=			=			=			=	
	$\%_A$	79.17	13.64	8.33	8.33	58.33	33.33	33.33	58.33	9.09	50.00	4.35	45.83

$\%_B$	79.17	59.09	66.67	66.67	58.33	41.67	58.33	45.83	77.27	50.00	82.61	50.00

(NP: Non-parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

7.3. Gymnast Group between Foot Positions

7.3.1. Gymnast Group in Normal Foot Position

Overall, Gymnast group has the same sequential orders in Normal foot position as All groups from non-parametric tests by comparing these depending on directions and speeds. Therefore, it can be inferred that gymnasts have consistent orders of muscle reacting after their balance is being perturbed within the same directions in Normal foot position. The 1st reacting muscles are TA in Forward, GA in Backward, PL in Lateral and TA in Medial directions (Forward: TA - PL - GA, Backward: GA - PL - TA, Lateral: PL - TA - GA, Medial: TA - GA - PL in the orders from non-parametric tests) (Table 7.5).

Table 7.5: non-parametric and Frequency order test from Normal Foot Position of Gymnast group

Gymnast Group - Normal Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	**1**	**2**	3	3	2	1	2	1	3	1	3	2
	FO	**1, 2**		3		=			=			=	
	$\%_A$	60.42	34.04	6.38	6.52	29.79	65.96	20.83	75.00	4.26	60.42	7.50	33.33
	$\%_B$	60.42 35.42		59.57	69.57	46.81	65.96	47.92	75.00	57.45	60.42	67.50	43.75
Slow	NP	1	2	3	3	2	1	2	1	3	**1**	3	**2**
	FO		=			=			=		**1, 2**	3	
	$\%_A$	66.67	20.83	12.50	9.09	43.48	52.17	20.83	75.00	4.17	50.00	16.67	37.50
	$\%_B$	66.67	41.67	54.17	72.73	43.48	52.17	58.33	75.00	66.67	50.00 41.67	55.56	37.50
Fast	NP	**1**	**2**	3	3	2	1	**2**	1	**3**	1	3	2
	FO	**1, 2**		3		=			1	**2, 3**		=	
	$\%_A$	54.17	47.83	0.00	4.17	16.67	79.17	20.83	75.00	4.35	70.83	0.00	29.17
	$\%_B$	54.17 45.83		65.22	66.67	50.00	79.17		75.00	47.83 47.83	70.83	77.27	50.00

(NP: Non-Parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

Between non-parametric and Frequency tests, the orders are the same within relevant directions of platform movement (Forward Slow, Backward all speeds, Lateral Total & Slow, Medial Total & Fast). However, $\%_B$ shows that TA can react as the 2nd reacting muscle as well as the 1st in Forward direction at Fast speed and Medial direction at Slow speed. These findings show slightly different results compared to non-parametric test ($\%_A$: averaged EMG latencies amongst trials were applied). TA is more disturbed to react firstly after having the Forward movement at Fast ($\%_B$: 54.17%) speed than Slow ($\%_B$: 66.67%) but this needs to react at least secondly even if other muscle reacts first (e.GA. PL) because TA is the main muscle which should work to maintain balance against the Forward platform movement. Oppositely, Fast speed helps TA to react more constantly as the 1st reacting muscle than Slow speed in Medial direction ($\%_B$ - F: 50.00% > S: 70.83%).

7.3.2. Gymnast Group in Turnout Foot Position

Overall, Gymnasts standing with Turnout foot positions have the same sequence orders of non-parametric test as the results from All groups depending on relevant directions and speeds apart from in Fast Forward platform movement (All group - FF: 'TA - PL - GA', Gymnast group - FF: 'TA - GA - PL') (Table 7.6). TA (Forward: 72.92%), PL (Backward: 54.17%), PL (Lateral: 54.17%) and TA & GA (Medial: 48.94% & 47.92%) are the 1st reacting muscles in each direction based on Total speed of Turnout position performed by Gymnasts.

Within directions, only the Medial direction shows different sequential orders between Slow and Fast platform movements that has the same orders as All groups (SM: 'TA - GA - PL', FM: 'GA - TA - PL'). This difference may be caused because Gymnasts use TA more than GA as the 1st reacting muscle to control balance during Slow Medial movement (65.22%). However, GA reacts first with 62.50 % during Fast Medial movement.

There are many minor differences between non-parametric and Frequency order tests in the Forward, Backward and Lateral directions at Slow speed. The 2nd and 3rd reacting muscles in Slow Forward directions from non-parametric test (GA [2nd] - PL [3rd]) are switch the orders from Frequency order test (PL [2nd] - GA [3rd]). This probably happens because Slow speed allows gymnasts to vary balance control after the 1st muscle is ON that means EMG latencies are more varied from PL and GA. Therefore, the orders from averaged EMG latencies (non-parametric test) may not show the same orders as Frequency order test.

Table 7.6: non-parametric and Frequency order test from Turnout Foot Position of Gymnast group

Gymnast Group - Turnout Foot Position													
Directions of Platform		**Forward**			**Backward**			**Lateral**			**Medial**		
Muscles		**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**	**TA**	**PL**	**GA**
Total	NP	1	**3**	**2**	3	1	2	**2**	**1**	3	**1**	**3**	**2**
	FO	1		**2, 3**		=			**1, 2**	3	**1, 2**	3	1
	$\%_A$	72.92	14.29	15.22	11.11	54.17	35.42	37.50	54.17	9.52	48.94	7.50	47.92
	$\%_B$	72.92		43.48 41.30	73.33	54.17	50.00		54.17 39.58	64.29	48.94 40.43	67.50	47.92
Slow	NP	1	**3**	**2**	**3**	**1**	**2**	**2**	**1**	3	1	3	2
	FO	1	**2**	**3**	3	1	1, 2		**1, 2**	3		=	
	$\%_A$	62.50	15.00	26.09	18.18	41.67	41.67	37.50	50.00	13.64	65.22	5.26	33.33
	$\%_B$	62.50	50.00	43.48	72.73	41.67	41.67 50.00		50.00 41.67	54.55	65.22	73.68	45.83
Fast	NP	1	3	2	3	1	2	2	1	3	**2**	**3**	**1**
	FO		=			=			=			=	
	$\%_A$	83.33	13.64	4.35	4.35	66.67	29.17	37.50	58.33	5.00	33.33	9.52	62.50
	$\%_B$	83.33	50.00	56.52	73.91	66.67	50.00	45.83	58.33	75.00	45.83	61.90	62.50

(NP: Non-Parametric test, FO: Frequency Order test, $\%_A$: Percentages of being the 1st reacting muscle, $\%_B$: Percentages to have their frequency orders, TA: Tibialis Anterior, PL: Peroneus Longus, GA: Gastrocnemius)

7.4. Dancers VS Gymnasts in Normal Foot Position

Both Dancer and Gymnasts groups have the same sequence orders from Total Normal foot position depending on each direction (Table 7.2 & Table 7.3). However, one of the main differences between the two groups can be that Gymnasts seem to have more variations to control balance than Dancers. This can be inferred because Frequency orders of Gymnasts are not perfectly the same as non-parametric test like Dancer group has. As mentioned earlier, having different orders between two tests may happen if EMG latencies are varied. Therefore, checking sequential orders in three muscles from only averaged EMG latencies (non-parametric test) might not include other characteristic facts which may be found from Frequency orders which are counted from every single trial. Therefore, discussing results from both non-parametric and Frequency order tests can be more sensible to explain details of balance control with different foot positions in each direction at each speed of platform movement.

Gymnasts can use GA more constantly as the 1st reacting muscle than Dancers in the Backward direction at Fast speed (Gymnast group: 79.17% > Dancer group: 54.17%). However, the percentage of the 1st reaction muscle in the Forward direction at Fast speed with Normal foot position is much higher from Dancer group than Gymnast group (Dancer group: 75.00% > Gymnast group: 54.17%). These findings might be due to their training methods, for example, Dancers have balance trainings with fully stretched knees and they need to land with their toes first then soles and heels then band knees. On the other hand, Gymnasts are probably less required to stretch their knees when they balance and they use whole part of soles when they land from the air. However, it is hard to simply describe the reasons of these findings for now.

Only Slow speed in the Forward direction from dancer has swapped non-parametric test's orders of the 2nd and 3rd reacting muscles compared with other speeds and also with Gymnast Group in the Forward direction (TA - GA - PL). Also, Frequency order test in the Forward direction at Slow speed has the same result as non-parametric one. This may happen because Dancers do not need to react PL quicker than GA during Forward platform movement at slow speed but they need to use

constantly TA, PL and GA as the 1st, 2nd and 3rd reacting muscles respectively. This can be seen from $\%_B$ in Fast Forward direction from Dancer group (TA [1st]: 75.00% - PL [2nd]: 69.57% - GA [3rd]: 82.61%) are a lot higher than in the Slow Forward direction (TA [1st]: 58.33% - GA [2nd]: 41.67% - PL [3rd]: 50.00%) and in the Fast Forward direction from Gymnast group (GA [1st]: 54.00% - PL [2nd]: 66.67% - TA [3rd]: 75.00%).

7.5. Dancers VS Gymnasts in Turnout Foot Position

With Turnout foot position, Dancers and Gymnasts have the same 1st reacting muscles by comparing within the same directions of platform movement apart from within the Medial direction (Forward: TA, Backward: PL, Lateral PL, Medial: GA & TA) (Table 7.3 & Table 7.5). Sequential orders from non-parametric tests are similar between two groups depending on directions at each speed. However, the Fast Forward platform movement has different orders (Dancer group FF: TA [1st] - PL [2nd] - GA [3rd], Gymnast group FF: TA [1st] - GA [2nd] - PL [3rd]) and the 2nd and 3rd reacting muscle places are opposite in the Medial direction at each speed between Dancer and Gymnast groups (the 3rd reacting muscle is always PL). Also, the percentages of the 1st reacting muscle ($\%_A$) at Slow movement from Dancer group are higher than from Gymnasts group in the Forward, Lateral and Medial directions. On the other hand, at Fast movement, the percentages of the 1st reacting muscles from Dancer group become smaller than from all groups apart from the Medial direction. This means that balance control of dancers can be less varied than gymnasts during Slow perturbation to Forward, Lateral and Medial directions in turnout foot. However, gymnasts are more likely to be better at using the 1st reacting muscles consistently to control their balance than dancers during fast perturbation in the Forward, Backward and Lateral directions.

The order from the Forward direction at Fast speed of Dancer group, which is different to Dancers in the Slow Forward movement and to Gymnasts in the Forward movement at each speed, affects the order of its Total speed as well. Comparing the percentages of the 1st reacting muscle (TA) in Forward direction at each speed between two groups, the percentage of TA from Dancer group at Slow speed is higher than from Gymnast group (Dancer group FS: 70.83% > Gymnast group FS: 62.50%) and Gymnast group's percentage of the 1st reacting (TA) muscle is greater than Dancer group's percentage (Dancer group FF: 79.17% < Gymnast group FF: 83.33%). These differences show that Dancers' balance control is more constant to use TA as the 1st reacting muscle during the Slow Forward movement with turnout foot than Gymnasts' balance control. On the other hand, Gymnasts are stronger to keep using TA as the 1st reacting muscles in the Forward direction at Fast speed with turnout foot than Dancers.

In the Backward direction of platform movement, both groups have the same sequential orders at any speeds from non-parametric test (PL [1st] - GA [2nd] - TA [3rd]). Overall, the percentages of the first reacting muscle (PL) from Gymnast group are larger than Dancer group (Total - Dancer group: 47.92% < Gymnast group: 54.17%, Slow - Dancer group: 37.50% < Gymnast group: 41.67%, Fast - Dancer group: 58.33% < Gymnast group: 66.67%). This means Gymnasts can use Peroneus muscle more constantly to control balance during the Backward platform movement. Furthermore, the percentages of frequency orders ($\%_B$) for the 2nd and 3rd reacting muscles are higher from Gymnast group than Dancer group at each speed including Total speed. Therefore, it can be inferred that Gymnasts have more constant balance control strategies than dancers with using the sequential order of PL, GA and TA in Backward platform movement with turnout foot.

During the Lateral direction of platform movement with turnout foot position, both groups have the same sequential orders from non-parametric test (PL [1st] - TA [2nd] - GA [3rd]). The percentages of the 1st reacting muscle (PL) from Dancer group is bigger than Gymnast group from Total speed and at Slow speed (Total - Dancer group: 64.58% > Gymnast group: 54.17%, Slow - Dancer group: 70.83% > Gymnast group: 50.00%, Fast - Dancer group: 45.83% < Gymnast group: 58.33%). This means that Dancers generally can use PL as the 1st reacting muscle more often than Gymnasts in the Lateral movement with turnout foot position but this muscle seems to be more disturbed at Fast movement from Dancer group than Gymnast group. Oppositely, Gymnasts are probably better to react PL as the 1st reacting muscle at Fast speed than at Slow speed.
Overall, the frequency order percentages of the 1st, 2nd and 3rd reaction muscles from Dancer group is greater than from Gymnasts apart from at Fast speed. Therefore, Dancers may also control their balance with more constant sequential orders than Gymnasts when the platform moves at Slow speed rather than Fast speed.

Both groups seem to have confusions between the 1st and 2nd reacting muscles as Tibialis and Gastro swap the sequential orders between the 1st and 2nd places depending on speeds (but opposite orders between groups). In Total, considering both speeds together, GA has slightly higher chance to be the 1st reacting muscle

than TA from Dancer group ($\%_A$ - GA: 50.00% > TA: 47.92) but TA is more likely to be the 1st reacting muscle than GA from Gymnast group with just 1.02% difference ($\%_A$ - TA: 48.94% > GA: 47.92%). These sequential orders are the same at Slow speed with small increases of percentages from Dancer group ($\%_A$ - GA: 54.17% > TA: 45.83%) but only the percentage of TA is greater at Slow speed compared to Total from Gymnast group ($\%_A$ - TA: 65.22% > GA: 33.33%).

Interestingly, the 1st reaction muscles are different between Slow and Fast speeds in the Medial direction from Gymnast group with higher percentages compared to other muscles ($\%_A$ - Slow TA [1st]: 65.22% > GA [2nd]: 33.33%, Fast GA [1st]: 62.50% > TA [2nd]: 33.33%). This means that Gymnasts generally use TA firstly at Slow speed but they depend on GA more at Fast speed as the 1st reacting muscle to control their balance in Medial direction. Oppositely, GA and TA are the 1st reacting muscles in Medial direction at Slow and Fast speeds respectively from Dancer group ($\%_A$ - Slow GA [1st]: 54.17% > TA [2nd]: 45.83%, Fast TA [1st]: 50.00% > GA [2nd]: 45.83%). The reason why these differences between the groups and speeds in Medial direction happen with turnout foot might be because of degrees of turnout foot.

7.6. Discussions

The related research questions are:

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

Generally, Dancers can stand with turned out foot more comfortably than Gymnasts as Dancers are trained to stand with turnout foot. In this case, both TA and GA may become important to react as the 1st muscles with similar percentages but more likely GA is the first at Slow speed and TA is the first at Fast from Dancer group with turnout foot. More turnout foot seems to make subjects to use the GA as 1st reaction muscle in the Medial direction at Slow and this conditions is similar to the Backward movement with Normal foot (GA reacts the first). However, it may possibly become hard to make GA reacts as the 1st muscle if the movement is Fast. With a similar principle, if the foot position is less turned out during the Medial direction, the 1st reaction muscle at Slow speed can be TA, which is relevant to the Medial direction with Normal foot position, but it changes to GA at Fast speed. These differences might occur because of different training skills to balance.

Dancers' TA muscle may have been trained to restore balance quicker. A research from Simmons (2005b) has found that EMG onset of TA from a dancer group was significantly quicker than from a non-dancer group which is the same finding as this study. Therefore, this can be emphasised that dancers have strong TA to control balance and this might be because of their training system. For example, they may face unbalanced situations which cause falling when they rise or kick another leg in various directions or degree. Yet, dancers do their best to keep stable even during dynamic conditions so this kind of training method in dance may develop dancers' TA more strongly and allow them to be able to react quicker in case of falls.

CHAPTER 8

JOINT TORQUE RESPONSES FROM SINGLE LEG BALANCE IN DYNAMIC CONDITIONS

This Chapter presents the results and discussion of 3D joint torque responses from single leg balance in dynamic conditions from the 3rd study: Comparisons of balance control and response to perturbations in single leg standing dance positions between dancers and gymnasts. Torque responses were calculated from the initiation of the platform movement to the first visible torque change from each trial. Statistical analyses of torque responses from the 3rd study are explained in Chapter 3.

This Chapter 7 is linked to research question Five and Six:

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

8.1. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis from both Dancer and Gymnast Groups

A four-way mixed ANOVA was used for the statistics analysis of the fastest joint torque responses. The test was ran separately on the fastest torque response amongst all nine joint torques ($Ankle_X$, $Knee_X$, Hip_X, $Ankle_Y$, $Knee_Y$, Hip_Y, $Ankle_Z$, $Knee_Z$ and Hip_Z) and Three joint torques from the main axis, which is expected to have the first torque response based on previous research in two dimensions (Forward & Backward directions: torque from X axis, Lateral & Medial directions: torque from Y axis).

8.1.1. Dancer Group vs Gymnast Group

There was no significant difference between groups from All Torques and Main Axis Torques (Table 8.1 & Figure 8.1). Interestingly, the torque response means of the gymnast group are longer than those from the dancer group in both All Torques and Main Axis Torque, which is similar to the result of EMG latencies in 6.1.1. Also the means of Main Axis Torque show longer delays than from All Torques. This result shows that it is possible to get quicker response from axes of torque other than the Main Axis Torque.

Table 8.1: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst All Torques and Main Axis Torques between Dancer and Gymnast groups

		Dancer Group	Gymnast Group	Sig.
All Torque	**Mean**	149.81	152.32	0.56
	SE	2.96	2.96	
Main Torque	**Mean**	160.18	164.47	0.37
	SE	3.24	3.24	

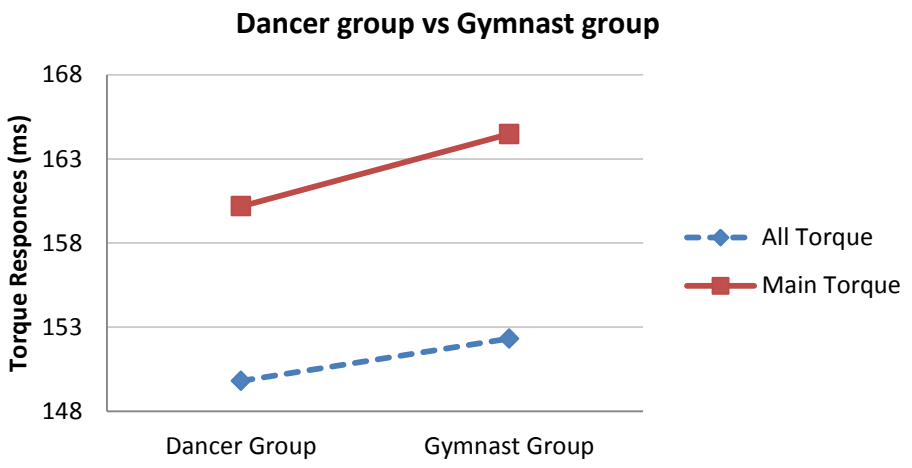


Figure 8.1: Mean graphs of All and Main Torque Responses (ms) and comparison between Dancer and Gymnast groups

8.1.2. Foot Positions

No significant differences were found between foot positions (Table 8.2 & Figure 8.2). Both All and Main axis torque means show that subjects seem to respond quicker in turnout foot position than in normal foot position. As expected this result is parallel to the result of EMG latencies between Normal and Turnout foot positions from All EMG sensors in 6.1.2.

Table 8.2: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst all torques and main axis torques between Normal and Turnout positions

		Normal Foot	Turnout Foot	Sig.
All Torque	**Mean**	153.11	149.02	0.16
	SE	2.22	2.77	
Main Torque	**Mean**	163.93	160.72	0.30
	SE	2.90	2.54	

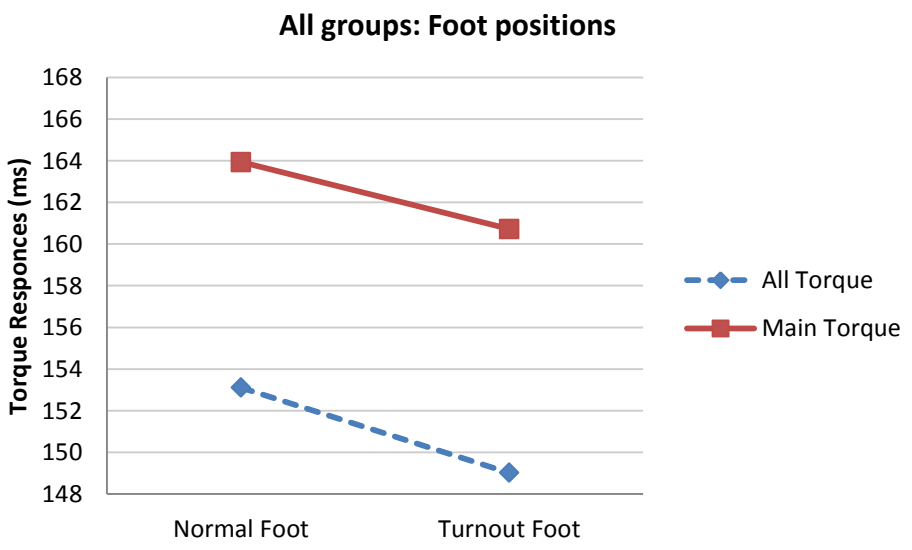


Figure 8.2: Mean graphs of All and Main Torque Responses (ms) and comparison between Normal and Turnout foot positions

8.1.3. Directions of Platform movement

The fastest torque responses amongst both All torques and Main axis torques have similar relationships of significance as in the comparisons between directions (Forward vs Backward, Backward vs Lateral) (Table 8.3 & Figure 8.3).

Backward direction of the platform, which causes subjects to start falling mainly forwards, has the fastest torque response. However, Forward direction, during which the body should start falling mainly backwards, shows the longer delays of torques. It can be inferred from these findings that it is easier to respond quicker when the body falls forward (backward platform movement) than backward (forward platform movement) and this may be due to the foot structure since the foot is pointing forward and has a larger BOS forward of the ankle. Dancers are often taught by coaches to put their body weight a bit forward when they land or pause after turns or jumps and the findings here can support the reason why dancers (probably gymnasts as well) should usually place their weight slightly forward after having a significant disruption of balance. However, all subjects could recover their balance when falling back from Forward direction of platform movement without fail during the experiment. This seems to happen because the body is trained to sway back and forth is able to recover from falling backward.

Lateral direction was the most challenging direction for the subjects to balance and this can be the reason why the fastest torques responses from Lateral direction were slower.

Table 8.3: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement

		Forward	Backward	Lateral	Medial
All Torque	**Mean**	156.37	144.45	153.52	149.91
	SE	3.28	3.53	3.67	2.46
	Sig.	B **0.013***	F **0.013***	F 0.390	F 0.093
		L 0.390	L **0.039***	B **0.039***	B 0.249

		M	0.093	M	0.249	M	0.473	L	0.473
Main Torque	**Mean**	165.36		153.90		168.27		161.77	
	SE	3.64		3.39		4.24		4.48	
	Sig.	B	**0.036***	F	**0.036***	F	0.500	F	0.514
		L	0.500	L	**0.035***	B	**0.035***	B	0.203
		M	0.514	M	0.203	M	0.203	L	0.203
Mean Diff All vs Main		8.99		9.45		14.75		11.86	

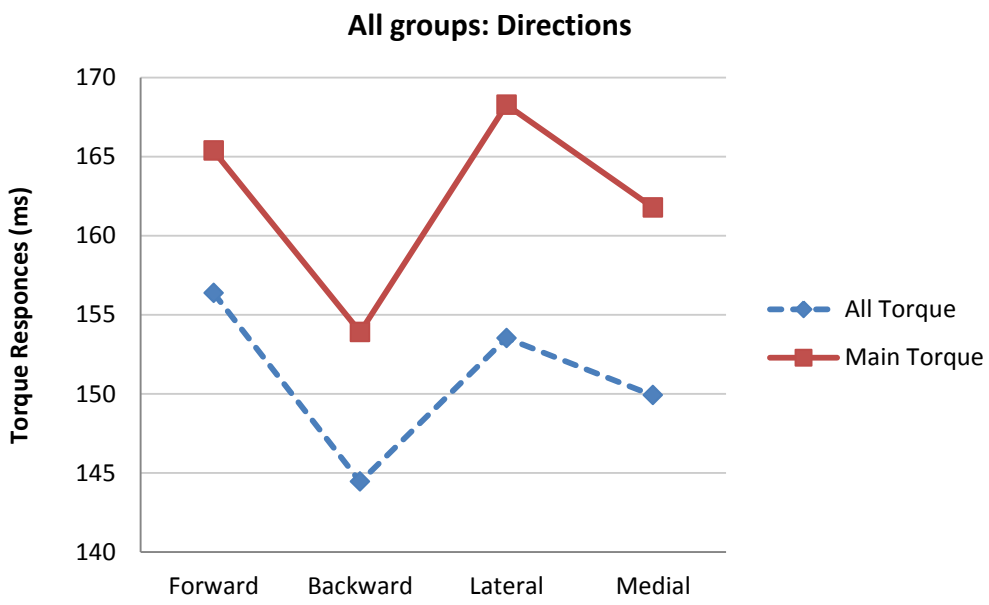


Figure 8.3: Mean graphs of All and Main Torque Responses (ms) depending on four direction of platform movement

8.1.4. Speeds of Platform Movement

Significant differences were found by comparing the speeds from fastest torques of the main axis (p=0.001) (Table 8.4 & Figure 8.4). This is similar to the finding from EMG latencies depending on the speeds of platform movement in 6.1.4.

Also, the fastest torque responses amongst all torques have the similar results (quicker response at Fast platform movement) but comparisons did not reach the level of significance.

As the main axis of torque is expected to depend mostly on a certain direction of platform movement, it responds more obviously depending on the perturbation speeds than other torque axes. Moreover, slow platform movement may not be strong enough for torques on the main axis to respond as the first during single leg stance. For example, the ankle may do adduction or abduction first at slow Forward or Backward platform movement before actually being ready to recover balance at ankle joint torque on X axis. Moreover, this could have been found because 3D inverse dynamics could calculate torques around other axes too as well as around the main axis.

Table 8.4: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and Total speeds of platform

		Total (S + F)		Slow		Fast	
All Torque	**Mean**	151.06		154.27		147.87	
	SE	2.09		2.80		2.47	
	Sig.	Slow	0.066	Total	0.066	Total	0.068
		Fast	0.068	Fast	0.067	Slow	0.067
Main Torque	**Mean**	162.29		168.84		155.844	
	SE	2.30		3.16		2.38	
	Sig.	Slow	**0.001***	Total	**0.001***	Total	**0.001***
		Fast	**0.001***	Fast	**0.001***	Slow	**0.001***

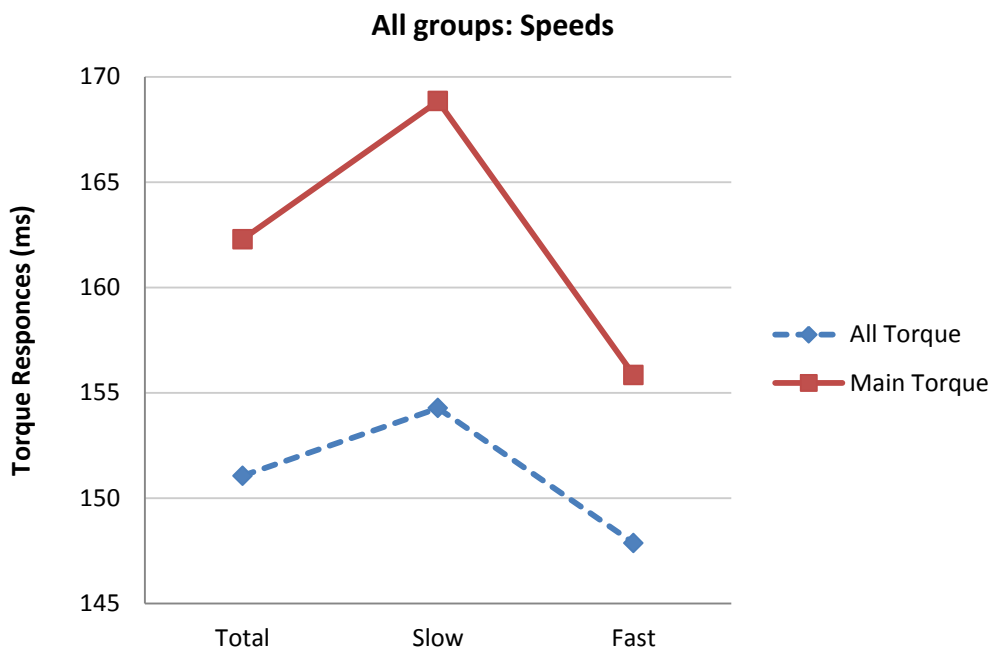


Figure 8.4: Mean graphs of All and Main Torque Responses (ms) depending on speeds of platform movement

8.2. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis based on the separated Dancer and Gymnast Groups

A three-way mixed ANOVA was used to check significant differences in Foot position, Directions of platform movement and Speeds of platform movement within separated Dancer group and Gymnast Group.

8.2.1. Foot Positions

There was no significant difference between Normal and Turnout foot positions from either group. Torque responses amongst All joint torques and Main axis joint torques were quicker during Turnout foot position compared to Normal foot position in both Dancer and Gymnast groups. From the results of fastest torque response among All nine joint torques, dancers seem to be able to respond quicker during Turnout foot single leg stance than during Normal foot condition and the same was noticed for gymnasts (Table 8.5 & Figure 8.5). Dancers get used to performing in turnout position so it seems to be easier for dancers to balance with a turned out foot and they can therefore respond really quickly.

Table 8.5: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques between Normal and Turnout positions based on separated groups

			Normal Foot	Turnout Foot	Sig.
Dancer Group	**All Torque**	**Mean**	153.56	146.06	0.150
		SE	3.44	4.49	
	Main Torque	**Mean**	161.35	159.02	0.493
		SE	4.05	3.77	
Gymnast Group	**All Torque**	**Mean**	152.66	151.98	0.831
		SE	2.80	3.25	
	Main Torque	**Mean**	166.52	162.42	0.436
		SE	4.15	3.41	

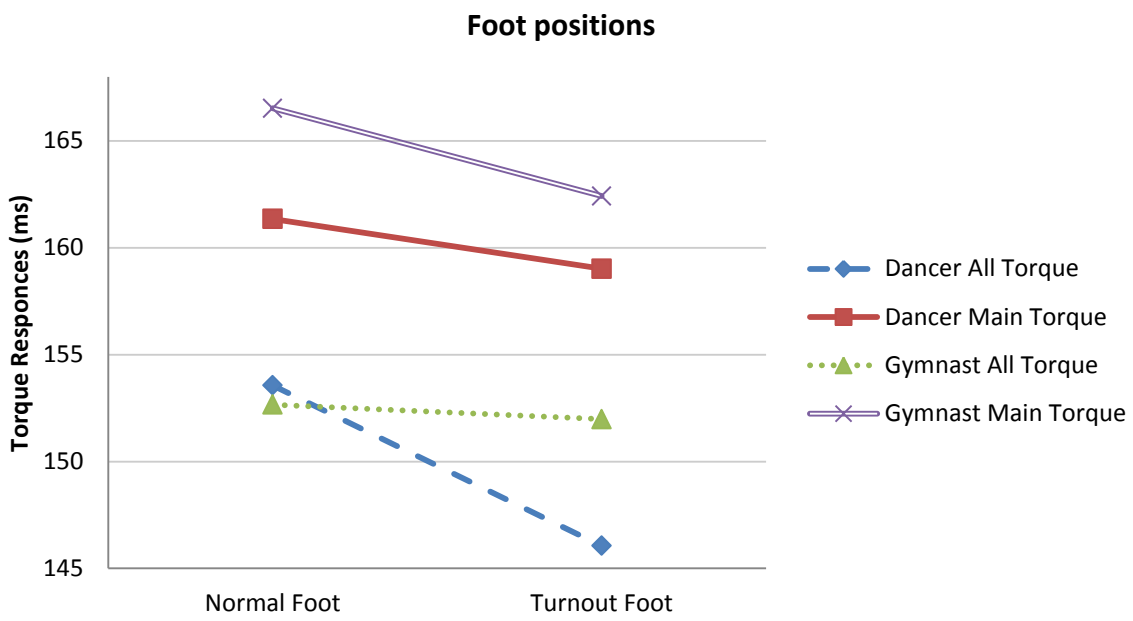


Figure 8.5: Mean graphs of All and Main Torque Responses (ms) and comparison between Normal and Turnout foot positions in separated groups (Dancers and Gymnasts)

8.2.2. Directions of Platform Movement

Significances were found between 'Forward vs Backward' and 'Backward vs Lateral' platform movements from fastest torques of Gymnast group (Table 8.6 & Figure 8.6). As expected, the results show similar relationships as the combined group's platform direction comparisons (four-way mixed ANOVA) in 8.1.3. As there was no significant difference in comparisons between directions from Dancer group, the results from Gymnast group may affect the comparisons of directions from combined group to have significant differences in 8.1.3.

Overall, all the fastest joint torques have fastest response after Backward direction. Hence, Forward and Lateral platform movements cause much longer torque responses compared to other two directions (Backward and Medial).

Table 8.6: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement based on separated Dancer and Gymnast groups

			Forward	Backward	Lateral	Medial
Dancer Group	**All Torque**	**Mean**	153.34	144.81	151.68	149.41
		SE	5.18	5.29	6.18	4.00
		Sig.	B 0.231	F 0.231	F 0.767	F 0.447
			L 0.767	L 0.329	B 0.329	B 0.577
			M 0.447	M 0.577	M 0.786	L 0.786
	Main Torque	**Mean**	162.85	154.09	162.78	161.01
		SE	6.00	4.97	6.12	5.62
		Sig.	B 0.311	F 0.311	F 0.989	F 0.727
			L 0.989	L 0.385	B 0.385	B 0.482
			M 0.727	M 0.482	M 0.708	L 0.708
Gymnast Group	**All Torque**	**Mean**	159.40	144.09	155.37	150.42
		SE	4.01	4.69	3.95	2.92
		Sig.	B **0.022***	F **0.022***	F 0.280	F 0.131
			L 0.280	L **0.042***	B **0.042***	B 0.204
			M 0.131	M 0.407	M 0.407	L 0.407
	Main Torque	**Mean**	167.88	153.72	173.75	162.54
		SE	4.12	4.62	5.86	7.12
		Sig.	B **0.044***	F **0.044***	F 0.431	F 0.589
			L 0.431	L **0.041***	B **0.042***	B 0.262
			M 0.589	M 0.262	M 0.234	L 0.234

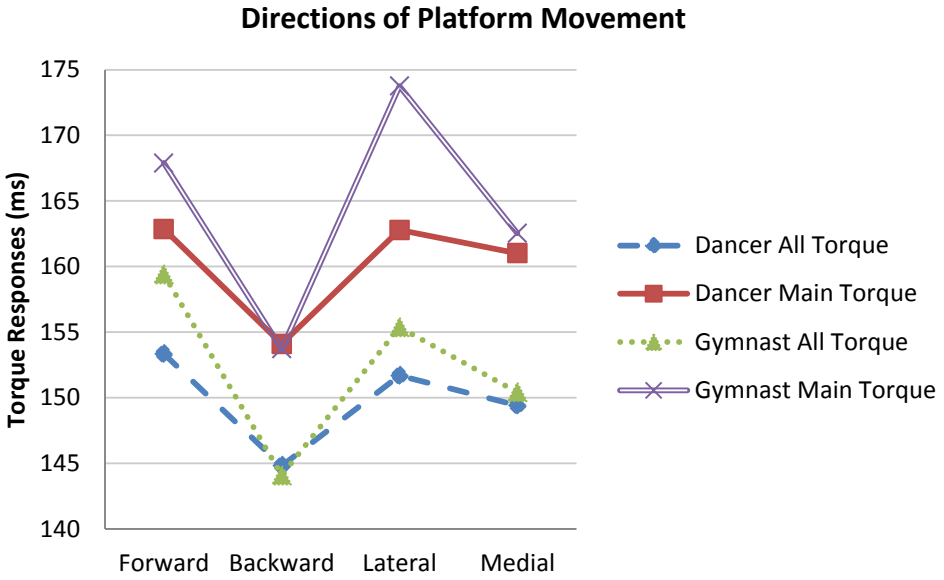


Figure 8.6: Mean graphs of All and Main Torque Responses (ms) and comparison between four directions in separated groups

8.2.3. Speeds of Platform Movement

From both groups, the subjects seem to respond quicker to Fast platform movements than Slow platform movement (Table 8.7 & Figure 8.7). However, there was no significant difference found from Dancer group. Significances were only found between the speeds from Main axis joint torques of Gymnasts group (p=0.007). This means that Gymnasts are able to respond quicker to Fast platform movement than to Slow platform movement but Dancers might not always be able to respond fast enough to Fast movement. This could be because of their training conditions as Gymnasts get use to recover balance from fast falls after landing. The finding that torque responses are quicker to Fast platform movement than to Slow movement supports the result of fastest EMG latencies from Gymnast group in 6.3.3. On the other hand, the fastest EMG latencies were slower at Fast speed than at Slow from Dancer group (in 6.2.3) which are not irrelevant to the fastest joint torque responses. However, these results do not have any significant difference in their comparisons so may not be considered as an important finding.

Table 8.7: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds of platform based on separated groups

			Total (S + F)		Slow		Fast	
Dancer Group	**All Torque**	**Mean**	149.80		150.43		149.21	
		SE	3.27		3.75		3.95	
		Sig.	Slow	0.768	Total	0.768	Total	0.784
			Fast	0.784	Fast	0.776	Slow	0.776
	Main Torque	**Mean**	160.11		163.22		157.22	
		SE	3.59		3.56		4.44	
		Sig.	Slow	0.147	Total	0.147	Total	0.170
			Fast	0.170	Fast	0.158	Slow	0.158
Gymnast Group	**All Torque**	**Mean**	152.32		158.12		146.52	
		SE	2.62		4.16		2.97	
		Sig.	Slow	0.053	Total	0.053	Total	0.053
			Fast	0.053	Fast	0.053	Slow	0.053
	Main Torque	**Mean**	164.47		174.47		154.47	
		SE	2.87		5.23		1.70	
		Sig.	Slow	**0.007***	Total	**0.007***	Total	**0.007***
			Fast	**0.007***	Fast	**0.007***	Slow	**0.007***

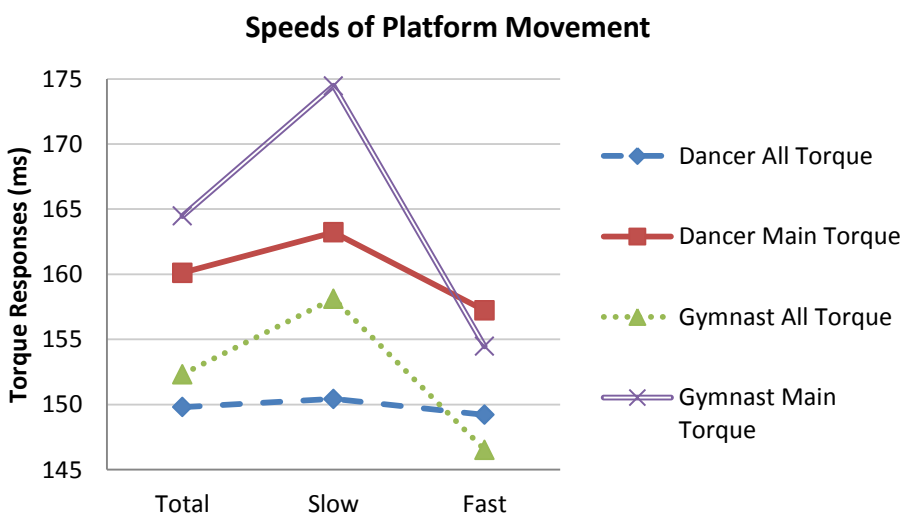


Figure 8.7: Mean graphs of All and Main Torque Responses (ms) and comparison between the speeds of platform movement in separated groups

8.3. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis in Normal Foot position based on separated Dancer and Gymnast Groups

A two-way Repeated Measures ANOVA was used to check significant differences in Normal foot position only within separated Dancer group and Gymnast Group. Directions and Speeds of platform movement were compared in Normal foot position.

8.3.1. Normal Foot: Directions of Platform Movement

There was no significance found in Dancer group by comparing the fastest torque responses between directions during Normal foot position (Table 8.8 & Figure 8.8). In Gymnast group, 'Backward vs Medial (All Torque)' and 'Backward vs Lateral (Main Torque)' show significant differences. The fastest torque responses among Main axis torque in Normal foot position show similar relationships between directions to combined foot position results in 8.2.2. However, the fastest torque amongst All torque during Normal foot & Backward direction is significantly different to Medial direction. This seems to indicate that Medial direction was probably the 2nd most challenging direction to recover balance and Gymnasts probably have their strategies to keep balance from their training.

Table 8.8: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement of Normal foot position based on separated Dancer and Gymnast groups

			Forward	Backward	Lateral	Medial
Dancer Group	All Torque	Mean	154.75	145.91	155.92	157.66
		SE	9.87	3.65	6.85	4.93
		Sig.	B 0.455	F 0.455	F 0.901	F 0.801
			L 0.901	L 0.264	B 0.264	B 0.200
			M 0.801	M 0.200	M 0.843	L 0.843
	Main Torque	Mean	164.39	153.32	165.03	162.64
		SE	11.40	4.56	8.48	5.51
		Sig.	B 0.420	F 0.420	F 0.962	F 0.888

			L 0.962	L 0.354	B 0.354	B 0.346
			M 0.888	M 0.346	M 0.734	L 0.734
Gymnast Group	**All Torque**	**Mean**	158.62	143.52	155.68	152.81
		SE	3.75	4.80	7.96	5.03
		Sig.	B 0.069	F 0.069	F 0.710	F 0.508
			L 0.710	L 0.238	B 0.238	B **0.041***
			M 0.508	M **0.041***	M 0.781	L 0.781
	Main Torque	**Mean**	164.84	154.82	177.59	168.82
		SE	4.33	5.63	8.71	10.68
		Sig.	B 0.276	F 0.276	F 0.310	F 0.793
			L 0.310	L **0.040***	B **0.040***	B 0.127
			M 0.798	M 0.127	M 0.445	L 0.445

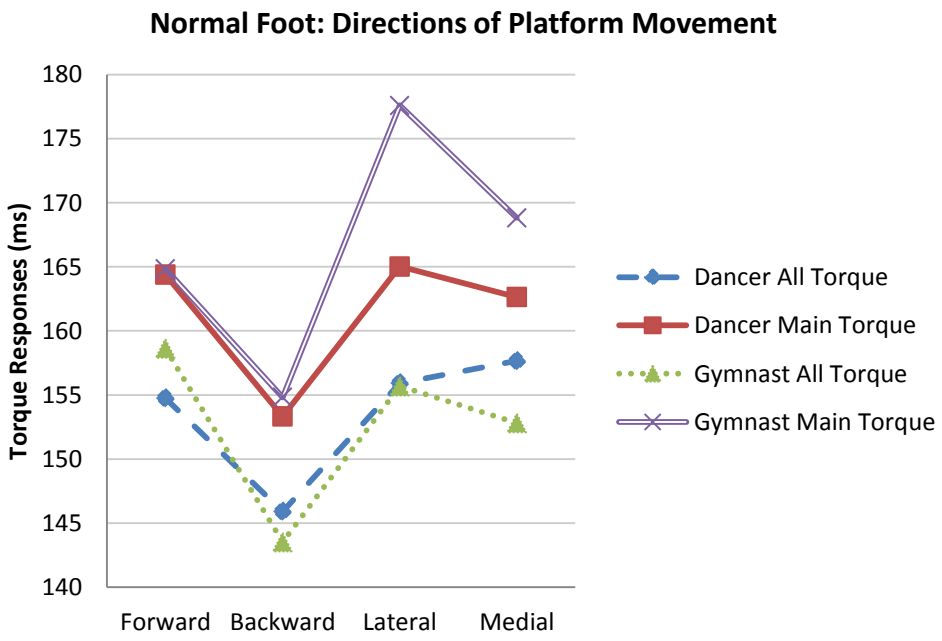


Figure 8.8: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups

8.3.2. Normal Foot: Speeds of Platform Movement

Overall, all comparisons between speeds show that torque responses were quicker at Fast speed than at Slow speed. Significant differences were found from All Torque Dancer Group and Main Torque Gymnast Group (Table 8.9 & Figure 8.9). Other comparisons do not show significant difference but these are close to be significant. It is expected to have all significant differences between speeds if there are more numbers of trials or subjects.

Table 8.9: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds platform movement in Turnout foot position based on separated groups

			Total (S + F)		Slow		Fast	
Dancer Group	**All Torque**	**Mean**	153.53		157.75		149.40	
		SE	3.45		3.57		3.66	
		Sig.	Slow	**0.007***	Total	**0.007***	Total	**0.007***
			Fast	**0.007***	Fast	**0.007***	Slow	**0.007***
	Main Torque	**Mean**	161.20		167.07		155.77	
		SE	4.09		5.44		3.85	
		Sig.	Slow	0.055	Total	0.055	Total	0.054
			Fast	0.054	Fast	0.054	Slow	0.054
Gymnast Group	**All Torque**	**Mean**	152.66		160.33		144.98	
		SE	2.80		5.57		3.38	
		Sig.	Slow	0.074	Total	0.074	Total	0.074
			Fast	0.074	Fast	0.074	Slow	0.074
	Main Torque	**Mean**	166.52		177.60		155.44	
		SE	4.15		8.14		2.52	
		Sig.	Slow	**0.039***	Total	**0.039***	Total	**0.039***
			Fast	**0.039***	Fast	**0.039***	Slow	**0.039***

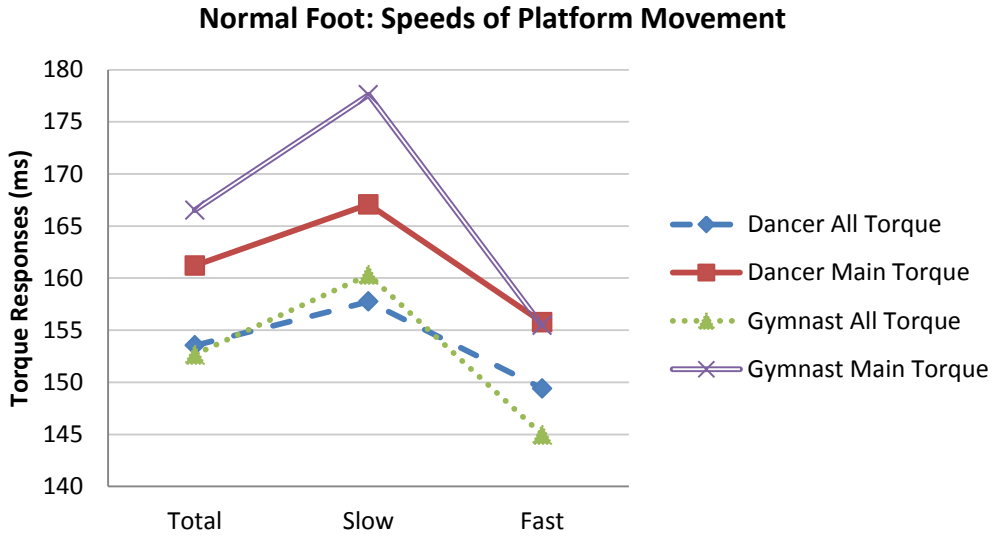


Figure 8.9: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups

8.4. The Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis in Turnout Foot position based on separated Dancer and Gymnast Groups

A two-way Repeated Measures ANOVA was used to check significant differences in Turnout foot position only within Dancer group and Gymnast Group separately.

8.4.1. Turnout Foot: Directions of Platform Movement

There were no significant differences in comparisons in separated Dancer and Gymnast groups during Turnout foot single leg stance (Table 8.10 & Figure 8.10).

Normally, Backward platform movement is supposed to have the quickest torque response amongst all direction (in 8.1.3, 8.2.2 and 8.3.1). Interestingly, Dancers seem to respond quicker in Turnout foot during Medial direction than in any other directions based on mean values. Dancers can probably perform more turned out foot position than Gymnasts so the condition of 'Turnout foot & Medial direction' becomes similar to 'Normal foot & Backward direction' (the platform is moving to the heel) (in 8.3.1). Overall, Dancers may respond quicker in Turnout foot position compared to Normal foot position and Gymnast groups has more variable torque responses.

Table 8.10: Mean and SE (Standard Error) values of Torque responses (in ms) amongst All Torques and Main axis Torques in four directions of platform movement of Turnout foot position based on separated Dancer and Gymnast groups

			Forward	Backward	Lateral	Medial
Dancer Group	**All Torque**	**Mean**	151.94	143.71	147.44	141.16
		SE	4.67	7.59	9.03	6.83
		Sig.	B 0.296	F 0.296	F 0.651	F 0.238
			L 0.651	L 0.696	B 0.696	B 0.807
			M 0.238	M 0.807	M 0.567	L 0.567
	Main	**Mean**	161.30	154.85	160.53	159.38

	Torque	**SE**	5.00	6.95	7.74	6.89
		Sig.	B 0.542	F 0.542	F 0.932	F 0.818
			L 0.932	L 0.592	B 0.592	B 0.676
			M 0.818	M 0.676	M 0.867	L 0.867
Gymnast Group	**All Torque**	**Mean**	160.17	144.67	155.05	148.02
		SE	6.96	7.80	3.76	3.35
		Sig.	B 0.193	F 0.193	F 0.542	F 0.152
			L 0.542	L 0.236	B 0.236	B 0.658
			M 0.152	M 0.658	M 0.131	L 0.131
	Main Torque	**Mean**	170.91	152.61	169.91	156.25
		SE	7.13	7.95	6.49	4.91
		Sig.	B 0.160	F 0.160	F 0.902	F 0.093
			L 0.902	L 0.186	B 0.186	B 0.695
			M 0.093	M 0.695	M 0.129	L 0.129

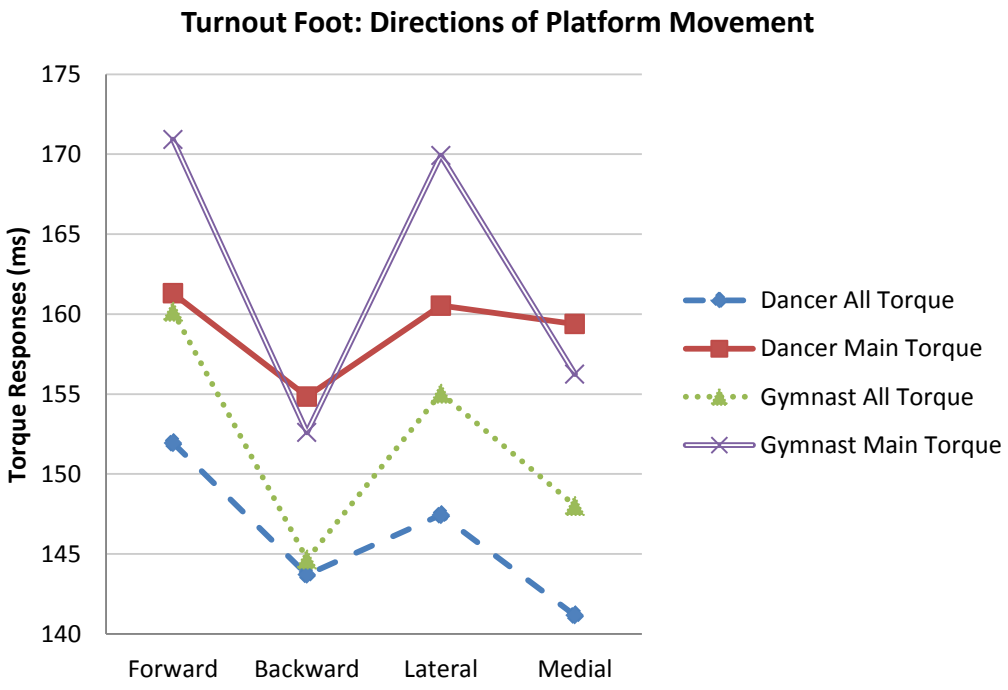


Figure 8.10: Mean graphs of All and Main Torque Responses (ms) in Normal foot position and comparison between the speeds of platform movement in separated groups

8.4.2. Turnout Foot: Speeds of Platform Movement

Slow and Fast platform movements were not significantly different in Turnout foot position (Table 8.11 & Figure 8.11). Therefore, it can be inferred that comparisons between speeds from combined group (in 8.1.4) and separated groups (in 8.2.3), which show torque responses to Fast are significantly quicker than to Slow speed, are due to results of Normal foot position not Turnout position.

By comparing means of the fastest torques, Gymnast group may respond slower than Dancer group but Gymnasts may have quicker torque responses to Fast speed than Dancers. Only Dancer group's fastest torque amongst All joint torques was slower at Fast speed than at Slow which means Dancers might have more difficulties to respond quick enough at Fast platform movement. However, torque responses of dancer All torque in Turnout foot position were generally quicker than in any other conditions and foot position.

Table 8.11: Mean and SE (Standard Error) values of Torque Responses (in ms) amongst Slow, Fast and combined Total speeds platform movement in Turnout foot position based on separated groups

			Total (S + F)		Slow		Fast	
Dancer Group	**All Torque**	**Mean**	146.06		143.10		149.02	
		SE	4.49		6.86		6.10	
		Sig.	Slow	0.548	Total	0.548	Total	0.548
			Fast	0.548	Fast	0.548	Slow	0.548
	Main Torque	**Mean**	159.02		159.37		158.67	
		SE	3.77		4.60		6.82	
		Sig.	Slow	0.940	Total	0.940	Total	0.939
			Fast	0.939	Fast	0.939	Slow	0.939
Gymnast Group	**All Torque**	**Mean**	151.98		155.90		148.05	
		SE	3.25		5.03		4.46	
		Sig.	Slow	0.296	Total	0.296	Total	0.296
			Fast	0.296	Fast	0.296	Slow	0.296
	Main	**Mean**	162.42		171.34		153.49	

	Torque	**SE**	3.41		6.32		3.69	
		Sig.	Slow	0.056	Total	0.056	Total	0.056
			Fast	0.056	Fast	0.056	Slow	0.056

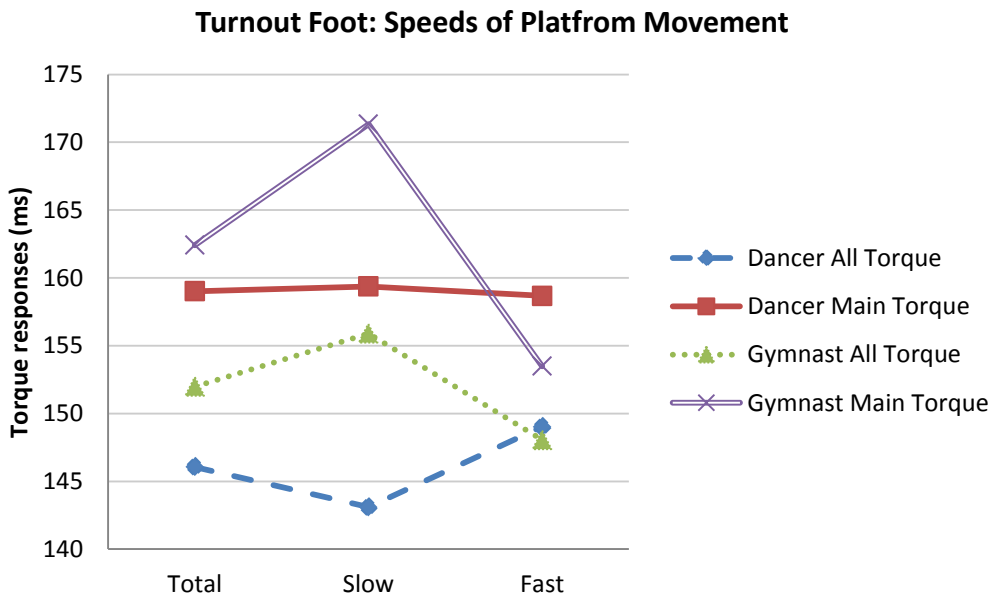


Figure 8.11: Mean graphs of All and Main Torque Responses (ms) in Turnout foot position and comparison between the speeds of platform movement in separated groups

8.5. Comparisons of the Fastest Joint Torque Responses amongst All 9 Joint Torques (Three axes & Three Joints) and 3 Joint Torques from the Main axis between Dancer and Gymnast Groups (Independent samples T-test)

Independent samples T-test was used to compare the fastest torque responses of each case between Dancer and Gymnast Groups. Unexpectedly, there was no significant difference across the groups and the only results found to be close to the significant level were from Turnout foot position in Forward direction at Slow speed. Dancers may respond quicker than Gymnasts in Turnout foot single leg stance during Forward platform movement. This finding may support that Dancers can response quickly in Turnout foot positions, particularly during Slow Forward platform movement as Dancers get used to balance in this position and situation because of their dance training.

Table 8.12: Mean and SD (Standard Deviation) values of Torque responses amongst All torques and Main axis with Turnout foot position in Forward direction at Slow platform movement (Independent samples T test was used)

			Mean & SD (ms)	Dancer group	Gymnast group	Sig.
Turnout Forward	**All Torque**	**Slow**	Mean	141.96	172.86	0.063
			SD	21.91	37.38	
	Main Torque	**Slow**	Mean	158.83	187.10	0.077
			SD	18.49	37.52	

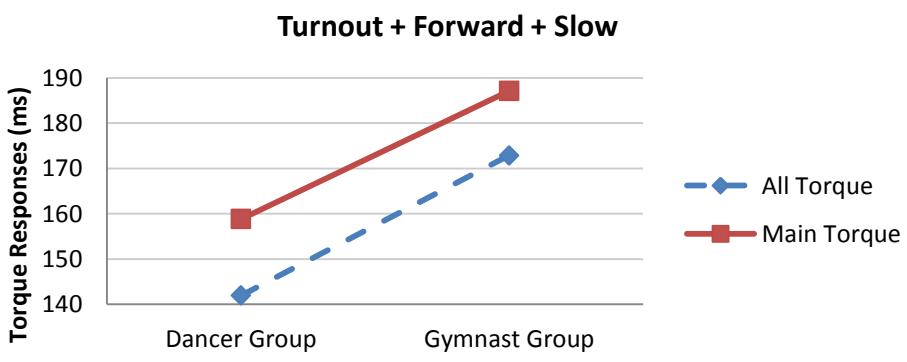


Figure 8.12: Mean graphs of All and Main Torque Responses (ms) in Turnout foot position + Forward Direction + Slow platform movement and comparison between the separated groups

8.6. Comparisons of torques in each condition between Dancer and Gymnast Groups (One-way ANOVA)

A one-way ANOVA was used for the statistics analysis of each nine joint torques ($Ankle_X$, $Knee_X$, Hip_X, $Ankle_Y$, $Knee_Y$, Hip_Y, $Ankle_Z$, $Knee_Z$ and Hip_Z) in each condition (Foot positions × Directions × Speeds) between the groups. There was no significance found from 'Normal Foot × Backward direction' between Dancers and Gymnasts. However, some interesting results were found with significances between groups in other conditions.

8.6.1. Dancer Group vs Gymnast Group: Normal Foot × Backward

There was a significant difference between the groups from $Ankle_Y$ at Fast platform movement and Gymnast group had quicker responses in this condition (Table 8.13). Moreover, Gymnasts could respond quicker compared to Dancers in $Knee_Y$ Fast speed condition. The Y axis is not the main axis of torque in Backward direction but Gymnasts response quicker than Dancers around Y torque axis of Ankle as well as Knee. This means Gymnasts can produce other joint torque fast enough after the torques of the main axis is being produced. No significance was found from X torque axis (the main axis) but Dancer group seems to response quicker than Gymnast group during Normal Foot & Backward platform movement.

Table 8.13: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Normal Foot × Backward' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Ankle	**X**	Total	**D**	**153.74**	11.49	4.06	0.084
			G	168.87	19.91	7.04	
Ankle	Y	Total	D	268.82	56.64	20.02	0.066
			G	**222.12**	51.24	12.10	
Ankle	Y	Fast	D	237.16	96.79	34.22	**0.041***
			G	**188.25**	33.23	11.75	
Knee	Y	Fast	D	346.02	116.24	41.10	0.061
			G	**251.44**	61.17	21.63	

8.6.2. Dancer Group vs Gymnast Group: Normal Foot × Lateral

Interestingly, all means of Gymnast group were smaller compared with Dancer group from comparisons which have significant differences or close to the p value (Table 8.14). The main torque axis in Lateral direction is the Y axis and Hip_Y Slow and Fast speeds show that Gymnasts use their hip quicker than Dancers to correct their balance during 'Normal Foot × Lateral'.

Balancing during Lateral platform movement in Normal Foot single leg stance was probably the hardest combination of 'direction × foot position' to control balance. Gymnasts certainly can respond Hip_Y quick enough and probably without regulating too much whereas Dancers are more highly trained to keep holding their hip stably while they are balancing. Also it was not only the Y torque axis, Gymnasts manage quicker joint torque responses about the Z axis than Dancers. Overall, it could be inferred that Gymnasts may perform better balance in 'Normal foot × Lateral' conditions than Dancers.

Table 8.14: Mean, SD (Standard Deviation) and SE values of joint torque responses in Normal Foot × Lateral' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Ankle	X	Fast	D	254.63	43.38	15.34	0.096
			G	**210.29**	55.42	19.59	
Hip	X	Fast	D	319.60	69.43	24.55	**0.001***
			G	**208.56**	31.64	11.19	
Knee	**Y**	Total	D	287.98	51.02	18.04	0.051
			G	**242.56**	31.92	11.29	
Knee	**Y**	Fast	D	278.61	57.18	20.22	0.062
			G	**220.27**	57.81	20.44	
Hip	**Y**	Total	D	276.96	59.14	20.91	**0.006***
			G	**198.80**	35.37	12.51	
Hip	**Y**	Slow	D	311.65	81.03	28.65	**0.046***
			G	**232.60**	61.82	21.86	
Hip	**Y**	Fast	D	242.27	86.26	30.50	**0.032***
			G	**165.00**	31.35	11.09	
Ankle	Z	Total	D	278.35	49.67	17.56	**0.001***
			G	**194.42**	34.19	12.09	

Ankle	Z	Slow	D	287.82	99.60	35.21	**0.028***
			G	**197.90**	29.99	10.60	
Ankle	Z	Fast	D	268.90	64.93	22.96	**0.014***
			G	**190.94**	44.20	15.63	
Knee	Z	Total	D	320.57	72.91	25.78	0.069
			G	**252.66**	64.51	22.81	
Hip	Z	Total	D	283.52	62.21	21.99	**0.020***
			G	**214.38**	41.46	14.66	

8.6.3. Dancer Group vs Gymnast Group: Normal Foot × Medial

Significant differences were found only from the X torque axis but not from the main one which is supposed to be the Y axis. Gymnasts responded earlier than Dancers especially around $Knee_X$ and Hip_X at Fast platform movement (Table 8.15).

Table 8.15: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Normal Foot × Medial' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Knee	X	Fast	D	254.60	50.98	18.03	**0.028***
			G	**200.23**	36.33	12.85	
Hip	X	Total	D	314.40	89.05	31.48	**0.038***
			G	**238.63**	28.45	10.06	
Hip	X	Slow	D	369.43	124.07	43.87	0.071
			G	**274.42**	59.81	21.14	
Hip	X	Fast	D	271.92	63.65	22.51	**0.016***
			G	**202.83**	31.84	11.26	

8.6.4. Dancer Group vs Gymnast Group: Turnout Foot × Forward

Significant differences support that Dancers could be better trained in Turnout position than Gymnasts (especially at Slow speed) and Dancers response from their $Ankle_X$ torque quickly is their main strategy during this condition. Moreover, 'Turnout × Forward' at Slow speed can be similar to Dancers balance training and this is the reason why Dancers are skilled at using their Ankle around the correct axis to keep their balance. However, Knee and Hip joint torques around the Y axis responded quicker from Gymnast group and Dancer group.

Table 8.16: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Forward' 'between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Ankle	**X**	Total	**D**	**169.46**	15.46	5.47	**0.044***
			G	188.86	19.35	6.84	
Ankle	**X**	Slow	**D**	**171.42**	22.66	8.01	**0.015***
			G	206.98	28.44	10.06	
Ankle	Y	Total	**D**	**210.59**	33.13	11.71	0.082
			G	251.66	52.31	18.50	
Knee	Y	Fast	D	221.60	20.93	7.40	0.087
			G	**202.69**	20.17	7.13	
Hip	Y	Fast	D	245.45	28.04	9.91	**0.027***
			G	**207.56**	33.23	11.75	

8.6.5. Dancer Group vs Gymnast Group: Turnout Foot × Backward

Significant differences were found between comparisons of groups from $Knee_X$ and Hip_X at Fast platform movement (Table 8.17). The mean of Dancer group is quicker than Gymnast group from $Knee_X$ but Gymnasts' Hip_X is quicker than Dancers. The quicker response of $Knee_X$ was not expected to have it from Dancer group. This finding might be caused because of knee extension not flexion, but this is only a speculation. Gymnasts are able to respond using their hip torque quickly around the X axis which means using the hip joint is important for Gymnasts to recover from balance disturbance in Turnout foot stance Fast Backward platform movement.

Table 8.17: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Backward' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Knee	**X**	Total	**D**	**198.16**	23.60	8.34	0.053
			G	232.22	38.98	13.78	
Knee	**X**	Fast	**D**	**204.04**	25.70	9.09	**0.015***
			G	243.17	30.44	10.76	
Hip	**X**	Fast	D	243.92	54.49	19.26	**0.029***
			G	**191.60**	26.75	9.46	
Ankle	Y	Total	**D**	**214.31**	27.39	9.68	0.084
			G	257.08	59.00	20.86	
Ankle	Y	Fast	**D**	**201.19**	18.30	6.47	0.088
			G	245.56	65.96	23.32	

8.6.6. Dancer Group vs Gymnast Group: Turnout Foot × Lateral

There was no significant difference found from the main torque axis (Y) but Gymnast group may possibly perform Hip strategy around Y torque axis much earlier than Dancer group (Table 8.18). All the significant comparisons, Gymnasts group have quicker torque responses than Dancer group around Hip_X, $Ankle_Z$ and Hip_Z at Fast movement. Comparing the means, Dancers might response quicker than Gymnasts with creating $Ankle_X$ and Kneex at Slow platform movement.

Table 8.18: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Lateral' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Ankle	X	Total	**D**	**218.27**	32.06	11.34	0.086
			G	264.81	63.66	22.51	
Ankle	X	Slow	**D**	**224.50**	43.50	15.38	0.089
			G	295.56	101.17	35.77	
Knee	X	Total	**D**	**221.53**	29.11	10.29	0.097
			G	248.38	31.31	11.07	
Knee	X	Slow	**D**	**234.06**	36.81	13.01	0.086
			G	274.12	49.19	17.39	
Hip	X	Total	D	304.54	83.04	29.36	**0.037***
			G	**229.76**	38.65	13.66	
Hip	X	Slow	D	313.42	92.90	32.85	0.088
			G	**246.31**	45.84	16.21	
Hip	X	Fast	D	295.67	94.26	33.33	**0.036***
			G	**213.21**	35.74	12.64	
Hip	**Y**	Slow	D	325.95	98.07	34.67	0.082
			G	**243.65**	76.25	26.96	
Ankle	Z	Total	D	266.36	59.20	20.93	**0.007***
			G	**194.88**	24.58	8.69	
Ankle	Z	Fast	D	307.25	125.96	44.53	**0.012***
			G	**175.36**	26.07	9.22	
Knee	Z	Total	D	284.30	75.36	26.64	0.074
			G	**226.25**	39.66	14.02	
Knee	Z	Fast	D	309.62	132.91	46.99	0.054
			G	**209.10**	25.85	9.14	
Hip	Z	Total	D	262.83	65.81	23.27	**0.043***
			G	**205.77**	30.07	10.63	
Hip	Z	Fast	D	283.09	91.48	32.34	**0.019***
			G	**188.71**	41.01	14.50	

8.6.7. Dancer Group vs Gymnast Group: Turnout Foot × Medial

Dancer and Gymnasts groups were significantly different from $Knee_X$, $Knee_Y$ and Hip_Z at Fast speed (Table 8.19). In this 'Turnout × Foot Medial' condition, Knee torque around X and Y axes may contribute a lot to keeping balance in the Gymnast group (probably by bending the knee joint as both the X and Y axes torque response times are similar). Unexpectedly, torque Hip_Z from Dancer group was significantly different to from Gymnast group. It is difficult to explain the reason for this finding, but it might not be an important fact as mean values are similar from both groups.

Table 8.19: Mean, SD (Standard Deviation) and SE values of joint torque responses in 'Turnout Foot × Medial' between the groups (Main axis depending on the platform movement and quicker means & group are in bold)

Joint	Torque axes	Speeds	Groups	Mean	SD	SE	Sig
Knee	X	Fast	D	264.94	74.16	26.22	**0.040***
			G	**201.40**	27.75	9.81	
Knee	**Y**	Fast	D	221.50	27.47	9.71	**0.030***
			G	**192.94**	19.05	6.73	
Hip	Z	Fast	**D**	**208.29**	39.02	13.80	**0.042***
			G	210.40	31.38	11.09	

8.7. Discussions

The related research questions are:

- Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

Generally, Turnout foot position had quicker mean Torque responses than Normal foot position from combined groups but these positions were not significantly different (p=0.16). The same comparison from EMG latencies in Chapter 6 shows that Turnout position was significantly quicker than Normal foot (p=0.034). This finding from Torque response is aligned with the finding from EMG latencies. Also, both EMG and Torque showed very similar resulting patterns during which subjects reacted and responded quicker to any direction of perturbation in Turnout foot single leg standing than Normal foot single leg standing. However, an interesting fact is that the significance values (Normal vs Turnout) can be different between EMG latencies (significant) and Torque responses (non-significant). Occurrence of EMG activation may not always mean that movement of segments around the joint will be followed. Therefore, there might be more complicated relationships between EMG latencies and Torque responses.

In terms of directions of platform movement, Torque response was significantly quicker at Backward direction compared to Forward (All Torque: p=0.013, Main Torque: p=0.036) and Lateral direction (All Torque: p=0.039, Main Torque: p=0.035) from combined groups, speeds, foot positions data. This finding is very different to EMG latencies which show Medial direction is significantly quicker than Forward direction in Chapter 6 (All EMG: p=0.033, Shank EMG: p=0.025).

Between two different speeds of platform movement, Fast platform movement caused significantly quicker Torque response compared to Slow platform movement

(p=0.001). Significant differences have not been found between the speeds for EMG latencies in Chapter 6.

Kiefer et al. (2013) reported that dancers performed more accurate joint position reproduction than non-dancers during a joint position matching task. Moreover, dancers had abilities to match ankle, knee and hip angles equally and accurately but non-dancers had more difficulties matching ankle joint positions accurately than knee and hip joints. These findings support that dancers may be better at and more sensitive to using proprioceptive information than non-dancers. On top of this, dancers have superior balance control skills around ankle joints from developing these skills to use proprioceptive information. By comparing the groups in this Chapter 8, Dancer group seems to be able to respond by prodcuing Torque quicker than Gymnast group, which is similar to the finding from EMG latencies in Chapter 6. Especially, Dancers have the quickest Torque response means in Turnout foot (All Torque: 146.06 ms / Main Torque: 159.02 ms) compared to Normal foot (All Torque: 153.56 ms / Main Torque: 161.35 ms) and Gymnasts (All Torque: Normal - 152.66 ms, Turnout - 151.98 ms / Main Torque: Normal - 166.52 ms, Turnout - 162.42 ms). Overall, Dancers had quicker Torque response during Turnout Slow but Gymnasts performed significantly quicker Torque responses at Fast platform movement than at Slow. Blaszczyk and Fredyk (2008) mentioned that the reason why Ballet dancers can perform perfect movement and postural control is because these abilities are developed by their professional training. Therefore, the finding, which Dancers can recover their balance in Turnout position, may be related to different training methods as dancers are standing on Turnout foot or feet during their performance and train slow balance control whereas gymnasts experience larger balance perturbations during their performance (e.g. landing).

Gymnasts were able to perform significantly quicker Torque response in Backward direction platform movement than in Forward (All Torque: p=0.022, Main Torque: p=0.044) and Lateral (All Torque: p=0.042, Main Torque: p=0.041) movements. Similarly, Torque response was quicker in Backward movement but significantly different compared to Medial (All Torque: p=0.041) or Lateral (Main Torque: p=0.040) in Normal foot position from Gymnast group. These significant differences were not found from EMG latencies (in Chapter 6) or from Dancer group. Torque response

from Backward direction was the quickest in all platform direction comparisons apart from Dancer Turnout All Torque (Medial was the quickest). Therefore, it can be highlighted that gymnasts have great balance skills to respond by producing torque quicker when backward perturbation happens (the body starts falling forward), especially, in Normal foot position. This must be related with gymnastics training as gymnasts stand on Normal foot position and often they need to place their body forward quickly when they have balance difficulties on landings or from fast limb motions.

The orders of Torque response (from the quickest) depending on the directions of platform movement were B < F < L < M from Dancers and B < M < L < F (All), B < F < M < L (Main) from Gymnasts in Normal foot position. In Turnout position, Dancers responded in the orders of M < B < L < F (All), B < M < L < F (Main) and Gymnasts had Torque response orders of B < M < L < F (All & Main). Significant differences were found only from Gymnasts in Normal foot position as mentioned in the previous paragraph. According to these findings, it can be discussed that both groups quickly started producing Torque around the joints in Backward direction compared to other directions. However, Dancers' Turnout position may result in a quicker response in the Medial direction than the Backward driection when all axes of joints are included. This may be due to having a more turned out foot position (more close to 90° laterally from normal foot fitting). In ballet, dancers are taught to produce Turnout position from their hip joint (not only the foot) thus dancers might have a characteristic balance method to control coordination after having perturbations. Moreover, both groups do not have the same orders for Torque response time within the directions. This means that each group has more preferred directions of perturbation which they can quickly respond to (or get used to) and these can be related to their training environment. For example, dancers may not often face the situation where their body is falling laterally (e.g. due to Medial platform movement) during Normal foot position because this is clearly not in their training. Firstly, dancers (especially ballet dancers) may not place the standing foot in this way. Secondly, dancers try to control the pronation around the ankle (inward) and avoid producing large amounts of supination. Therefore, dancers may not be trained to respond quickly enough if they need to control their balance in a situation which is similar to having Medial platform movement (falling lateral side).

By considering the means of Torque responses depending on speeds of platform movement, Dancers seem to respond quicker than Gymnasts at Slow platform movement. Oppositely, Gymnasts may respond quicker than Dancers at Fast platform movement (both All and Main). Therefore, Dancers are better at recovering balance by producing Torque quickly during Slow perturbation compared to Gymnasts but Gymnasts have quicker balance control at Fast platform movement than Dancers. Dancers seem to perform quicker Torque response at Turnout Forward Slow than Gymnasts (All torque: p=0.063, Main torque: p=0.077). This supports a finding from EMG part in Chapter 6 that Dancer group has a significantly quicker mean EMG latency than Gymnast group at Turnout forward Slow (from Shank muscles: p=0.016). Forward direction is harder to be balanced in Turnout than Normal foot. However, Dancers can respond quicker at (or during) slow perturbation while they are standing on Turnout foot because their way of training and environment in which dancers are required to balance during small balance perturbation. For example, ballet includes lots of Adagio movement which is raising or putting one leg down slowly and dancers need to balance on single leg with turnout position. The size of perturbation may be very similar to Slow speed platform movement in this study. It was reported from a research of Treman et al. (1994) that EMG activities of TA (29%) and Medial GA (54%) muscles increased above baseline during ballet first standing position (turnout) from Ballet and Modern dancer groups. Moreover, the study found that ballet dancers' TA EMG activity was more frequent than Medial GA compared to modern dancers. In Chapter 7, Non-parametric tests showed that TA is the quickest muscle to react after Forward platform movement during Turnout foot position (as well as Normal foot position) from both groups. Comparing both groups, Dancer group has a higher percentage of probability to have TA react first than Gymnast group in Turnout position at Slow Forward platform movement (Dancers: 70.83% vs Gymnasts: 62.50%). This also supports that TA muscle is very important and it reacts first at Slow Forward platform movement during Turnout position. Moreover, dancers are particularly good to balance during slow perturbation and when they have to bring their body forward after their body starts to fall backward (caused by Forward platform movement). Therefore, Torque response from dancers can be quicker than for gymnasts or even other populations

thanks to trained TA muscle and dancers have well-developed balance skills at slow perturbation.

By checking individual joints depending on axes and speeds, Gymnast group generally responds quicker if the platform movement is Fast or Foot position is Normal. Moreover, Gymnasts respond quicker with their Knee and Hip joints compared to Dancers. There are some exceptional cases, which Gymnasts' Ankle joint responds quicker than Dancers, but these axes are normally not the main expected axes (e.g. Forward and Backward platform movements: X axis is the main, Lateral and Medial platform movements: Y axis is the main). From Lephart et al. (1996)'s research evaluating knee kinesthesia (ability to detect passive motion) by using the proprioception testing device, Gymnasts had abilities to sense passive knee motion significantly quicker than non-gymnasts. Lephart et al. explained the reason might be because of comprehensive athletic training which helps enhancing neurosensory pathways and may give a positive effect on kinethesia due to rising muscle tone around joints.

In contrast, Dancers seems to perform quicker response than Gymnasts at Slow platform movement or in Turnout position. Generally, Dancers have quicker Ankle Torque response compared with Gymnasts. An interesting case is that when Torque from some axes of Knee (X, Backward platform movement) and Hip (Z, Medial platform movement) were quicker, Dancers were in Turnout position. This may happen because Dancers seem to strengthen and resist the joints during Turnout position. Compared to non-dancers, dancers' ankle-hip coordination is more stable (smaller SD angle: ankle relative to hip) and ankle-hip coupling less regulated (anti-phase: the ankle and hip are at opposite points in movement cycles) due to their flexibility and adaptability of the coordinative structures (Kiefer et al., 2011). Dancers can control complex balance by improving their stability through improved neuromuscular control and sensitivity of proprioceptive input (Lephart et al., 1996; Perrin et al., 2002; Kiefer et al., 2011).

Therefore, it can be emphasised from these findings of Torque that dancers and gymnasts may have different balance strategies. For instance, dancers may be

trained to rely on ankle strategy and gymnasts may be good to use hip strategy. Experiencing small sized perturbations may cause ankle strategy but hip strategy will happen if large perturbations occur (Winter, 1995). The finding can be explained with the previous research from Winter (1995) the reason why Dancer group quickly responds at Slow than Fast platform movement and Gymnast group is quicker to respond at Fast movement than Slow from this Chapter 8. Dancers may be trained to use ankle strategy first but gymnasts would more depend on hip strategy as the first response due to their training methods.

Both groups are well known to have really good balance skills compared to other sports groups. However, good balance control does not mean that balance is controlled in a same way and each event has its characteristic balance control to performers and balance control of performers may have been developed by the nature of the event (Voillerme et al., 2001). Understanding balance strategies for different sports or dances will help to improve more advanced skills and to prevent injuries as well.

CHAPTER 9

SINGLE LEG BALANCE CONTROL IN STATIC CONDITIONS

Results and discussions of 'the 3rd study: Comparisons of balance control and response to perturbations in single leg standing dance positions between dancers and gymnasts' is included in this chapter.

This Chapter 9 is linked to research question Four and Six:

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

- *Q6. What are the differences in balance control between Dancers and Gymnasts?*

The results from a Two-way ANOVA (between groups & between two foot positions - Normal vs Turnout) and paired T-test (within the groups: Normal Foot vs Turnout Foot) are described together. Static single leg balance on Demi-pointe has been removed from this analysis as there are some issues with analysing data from Demi-pointe positions because data was not taken for the full 30 seconds. This part is still in a development stage to find the best solution to analyse data and compare to other Foot positions.

9.1. Standard Deviation about the X axis, Medial-Lateral (SD_X)

There were some significant differences found from comparisons of the foot positions only (Table 9.1 & Figure 9.1). Mean SD_X values from Turnout position are much higher than from Normal foot position which means both Dancers and Gymnasts have wider range of corrections side to side while they are balancing on single leg in foot turnout. Humans generally sway in the Anterior - Posterior direction (AP) during quiet static balance which uses the ankle strategy and pivoting around Ankle's axis X. However, if the foot position is changed to Turnout, the subjects

increase sway movement in Medial-Lateral direction (ML) because they are still swaying using Ankle strategy.

There was no significant difference found between Groups.

Table 9.1: Means and SE (Standard Error) of Standard Deviations about the X (ML) axis (SD_X) from COP (Sig. < 0.05)

SD_X (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	4.51	0.508
			SE	0.35	
		Gymnast	Mean	4.85	
			SE	0.35	
	Foot positions	Normal	Mean	4.37	**0.001***
			SE	0.23	
		Turnout	Mean	4.98	
			SE	0.29	
Paired T Test	**Dancer Group**	Normal	Mean	4.22	**0.008***
			SE	0.25	
		Turnout	Mean	4.80	
			SE	0.30	
Paired T Test	**Gymnast Group**	Normal	Mean	4.53	**0.045***
			SE	0.38	
		Turnout	Mean	5.16	
			SE	0.50	

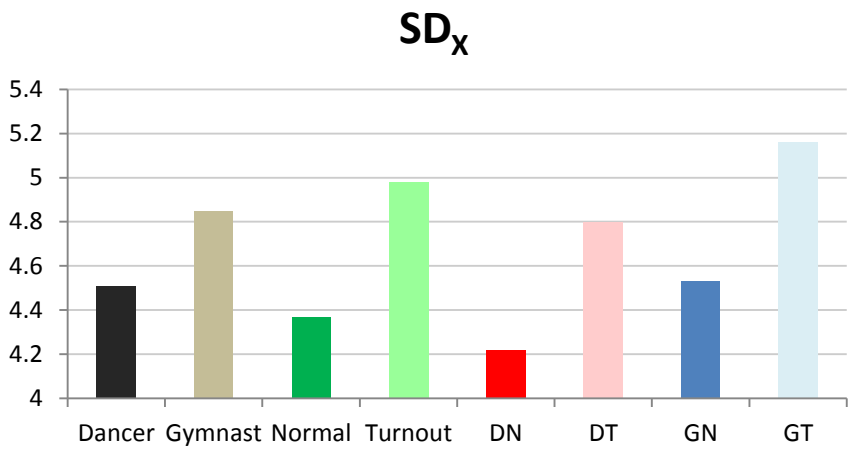


Figure 9.1: Comparisons of SD_X means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot]

9.2. Standard Deviation about the Y axis, Anterior-Posterior (SD_Y)

A significant difference was found between Foot positions for the whole group only (Two-way ANOVA). As the body sways back and forth, Normal foot positions have higher SD than Turnout foot positions about the Y axis. There was no significant difference found between groups.

Table 9.2: Means and SE (Standard Error) of Standard Deviations about the Y (AP) axis (SD_Y) from COP (Sig. < 0.05)

SD_y (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	5.68	0.911
			SE	0.30	
		Gymnast	Mean	5.73	
			SE	0.30	
	Foot positions	Normal	Mean	6.04	**0.018***
			SE	0.24	
		Turnout	Mean	5.37	
			SE	0.25	
Paired T Test	**Dancer Group**	Normal	Mean	6.09	0.051
			SE	0.19	

		Turnout	Mean	5.27	
			SE	0.37	
Paired T Test	**Gymnast Group**	Normal	Mean	6.00	0.186
			SE	0.44	
		Turnout	Mean	5.46	
			SE	0.34	

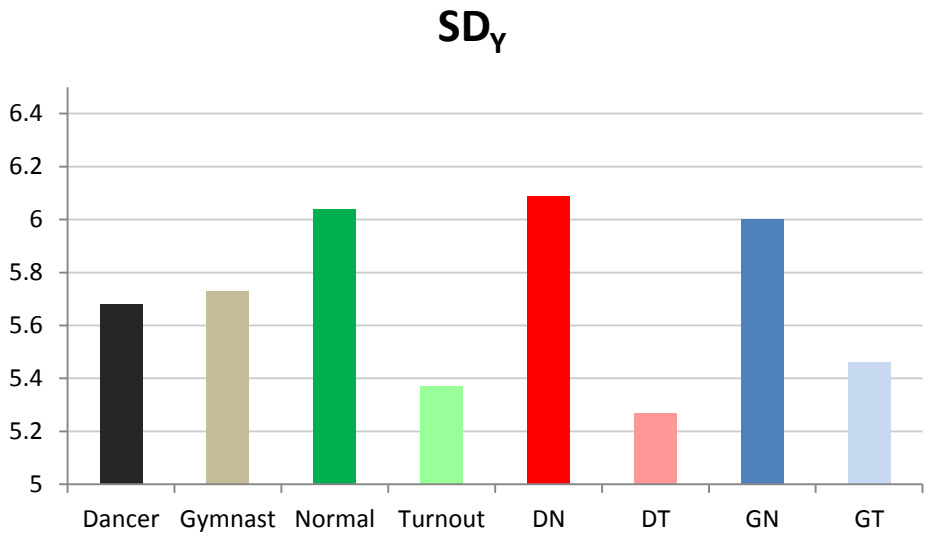


Figure 9.2: Comparisons of SD_Y means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot]

9.3. Range about the X axis of the COP, Medial-Lateral ($Range_X$)

Significant differences were found between Normal and Turnout foot positions (Table 9.3 & Figure 9.3). This finding also support that human body sways more in the same direction as where the foot is pointing (AP of the foot is placed parallel to the global X axis). In Turnout position, the foot is more turned out to the ML direction compared to Normal foot position and this is the reason why Range of COP increases around the X axis.

Table 9.3: Means and SE (Standard Error) of Range about the X (ML) axis ($Range_X$) from COP (Sig. < 0.05)

$Range_X$ (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	26.86	0.636
			SE	1.97	
		Gymnast	Mean	28.21	
			SE	1.97	
	Foot positions	Normal	Mean	25.76	**0.001***
			SE	1.25	
		Turnout	Mean	29.31	
			SE	1.65	
Paired T Test	**Dancer Group**	Normal	Mean	25.31	**0.029***
			SE	1.50	
		Turnout	Mean	28.41	
			SE	1.90	
Paired T Test	**Gymnast Group**	Normal	Mean	26.20	**0.023***
			SE	1.99	
		Turnout	Mean	30.21	
			SE	2.70	

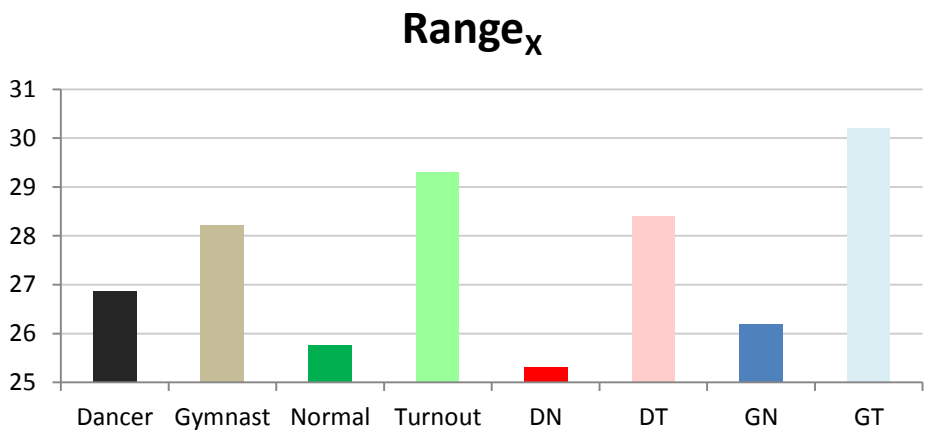


Figure 9.3: Comparisons of $Range_X$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

9.4. Range about the Y axis of the COP, Anterior-Posterior ($Range_Y$)

There were significant differences between the foot positions from Dancer group and from a comparison of combined groups (Table 9.4 & Figure 9.4). Dancer group had the greatest $Range_Y$ and the smallest $Range_Y$ from Normal foot position and Turnout foot positions respectively. It can be deduced that 1) Dancers perform large range COP movement in the direction where the foot is pointing by probably doing plantar-dorsiflexion (pivoting around X axis of ankle) and/or 2) Dancers have smaller range of ankle movement in ML direction of Ankle (Y axis of Ankle). Dancers seem to have better balance control in Turnout position relative to Normal condition than the Gymnast group.

Table 9.4: Means and SE (Standard Error) of Range about the Y (AP) axis ($Range_y$) from COP (Sig. < 0.05)

$Range_Y$ (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	32.74	0.966
			SE	2.14	
		Gymnast	Mean	32.87	
			SE	2.14	
	Foot positions	Normal	Mean	34.49	**0.008***
			SE	1.66	
		Turnout	Mean	31.12	
			SE	1.55	
Paired T Test	**Dancer Group**	Normal	Mean	34.85	**0.025***
			SE	2.32	
		Turnout	Mean	30.62	
			SE	2.29	
Paired T Test	**Gymnast Group**	Normal	Mean	34.13	0.161
			SE	2.38	
		Turnout	Mean	31.61	
			SE	2.10	

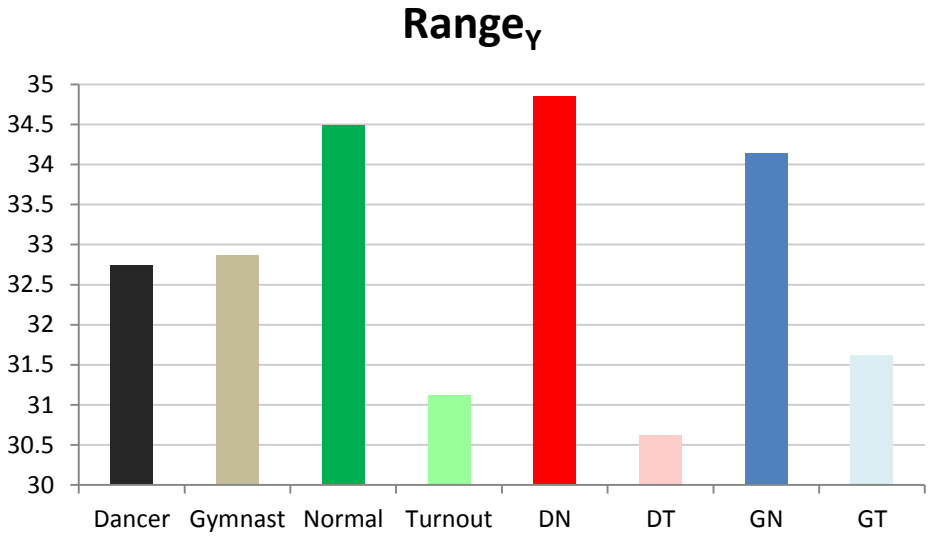


Figure 9.4: Comparisons of Range$_Y$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

9.5. Sway Path

No significant difference was found in comparisons of Sway Path (Table 9.5 & Figure 9.5). Mean values indicate that Dancer group had greater Sway Path than Gymnast group during single leg stance. However, each group has variations of Sway Path depending on each subject (DN: 2180-4823mm, DT: 2164-4792mm, GN: 2250-5046mm, GT: 2299-5233mm) so this finding is not really reliable. More subjects may be needed to determine the groups' characteristic in Sway Path.

Table 9.5: Means and SE (Standard Error) of from Sway Path (Sig. < 0.05)

Sway Path (mm)					Sig.
Two-way ANOVA	Groups	Dancer	Mean	3524.76	0.806
			SE	363.03	
		Gymnast	Mean	3396.25	
			SE	363.03	
	Foot positions	Normal	Mean	3443.13	0.196
			SE	257.60	
		Turnout	Mean	3477.88	
			SE	256.44	

Paired T Test	**Dancer Group**	Normal	Mean	3491.61	0.082
			SE	362.47	
		Turnout	Mean	3557.90	
			SE	349.51	
Paired T Test	**Gymnast Group**	Normal	Mean	3394.64	0.937
			SE	366.14	
		Turnout	Mean	3397.86	
			SE	375.34	

Both groups have longer Sway Path in Turnout position than Normal foot position. As Turnout position is one of the main foot positions, it was expected to have either shorter Sway Path (assumption 1: better control of static balance is shown by small movements) or longer Sway path (assumption 2: better balance means controlling balance movements within the broader safe boundaries, alternate theory) in Turnout than in Normal foot position. Dancer group has much longer Sway Path in Turnout position than in Normal foot position and the difference between the foot positions is larger than for the Gymnast group. Therefore, it can be inferred that dancers can perform better control of static balance by controlling their movements within the broader safe boundaries and this is the reason why dancers are able to control their balance during balance perturbations in Turnout foot position.

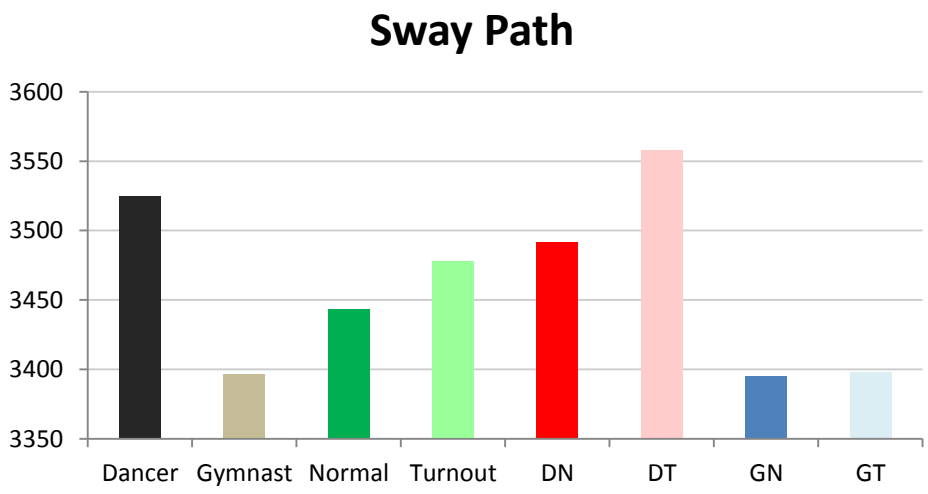


Figure 9.5: Comparisons of Sway Path means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

9.6. ApEn

Overall, Dancer group was more predictable than Gymnast group. There was no significant difference found between comparisons from groups or ApEn about the X axis (ML) but significant differences were found between Normal and Turnout foot positions about the Y axis (AP) ($p=0.001$) and from Dancer group ($p=0.004$) (Table 9.6, Figure 9.6 & Figure 9.7). Mean differences between Foot positions are similar and all Original ApEn values are between 1.041 to 1.124 mm which is a really small range of ApEn.

$ApEn_X$ (ML) is more predictable than $ApEn_Y$ (AP). However, $ApEn_X$ values from Dancer group's Turnout position and Gymnast groups' Normal position are slightly less predictable than its $ApEn_Y$. This may be linked to each group's enhanced direction during balance control. For instance, as it is shown in Chapters 5, 6 and 8, during dynamic conditions that Dancer group had quicker reaction, response in Turnout position than Normal foot position, dancers may have developed their balance control more in complicated way in Turnout position (because dancers train in Turnout foot) than Normal foot and dancers have their unique balance control in ML during Turnout single leg standing. Therefore, $ApEn_X$ became more complicated than other cases and even was slightly higher than $ApEn_Y$. On the other hand, gymnasts may have their characteristic balance control in ML direction by performing ankle pronation and supination while the foot is fitting normally and it results in having higher ApEn in ML than in AP during Normal footed single leg stance.

The ApEn values are higher than results found by Cavanaugh et al. (2007). The mean ApEn values from the research were 0.810±0.15 from single leg stance in AP direction and 1.006±0.21 in ML. The subjects were not specified into groups and they seem to have more unpredictable ApEn in ML than AP. Compared that research, both Dancers and Gymnasts have more unpredictable ApEn and it can be inferred that more skilled balancers may be higher ApEn which means balance control is more random, unpredictable and complex than less trained subjects.

All T-tests between Original ApEn and Surrogate ApEn show that these are significantly different (p≈0.00). Therefore, the Original ApEn is more predictable and less random than Surrogate ApEn.

Table 9.6: Means and SE (Standard Error) of ApEn (Sig. < 0.05)

$ApEn_X$ (mm)				Original	Sig.	Surrogate	Sig.	T test
Two-way ANOVA	**Groups**	Dancer	Mean	1.046	.693	1.308	.625	
			SE	0.039		0.042		
		Gymnast	Mean	1.068		1.338		
			SE	0.039		0.042		
	Foot positions	Normal	Mean	1.060	.660	1.324	.778	.000
			SE	0.028		0.030		
		Turnout	Mean	1.055		1.321		.000
			SE	0.028		0.030		
Paired T Test	**Dancer Group**	Normal	Mean	1.041	.291	1.308	.941	.000
			SE	0.038		0.043		
		Turnout	Mean	1.051		1.307		.000
			SE	0.038		0.045		
Paired T Test	**Gymnast Group**	Normal	Mean	1.078	.386	1.339	.773	.000
			SE	0.041		0.042		
		Turnout	Mean	1.058		1.335		.000
			SE	0.041		0.039		
$ApEn_Y$ (mm)								
Two-way ANOVA	**Groups**	Dancer	Mean	1.124	.736	1.377	.576	
			SE	0.085		0.097		
		Gymnast	Mean	1.083		1.288		
			SE	0.085		0.097		
	Foot positions	Normal	Mean	1.086	**.001**	1.320	.235	.000
			SE	0.061		0.066		
		Turnout	Mean	1.121		1.335		.000

			SE	0.060		0.071		
Paired T Test	**Dancer Group**	Normal	Mean	1.098	**.004**	1.366	.937	.000
			SE	0.084		0.091		
		Turnout	Mean	1.150		1.368		.000
			SE	0.084		0.104		
Paired T Test	**Gymnast Group**	Normal	Mean	1.074	.134	1.273	.094	.000
			SE	0.087		0.096		
		Turnout	Mean	1.091		1.302		.000
			SE	0.087		0.097		

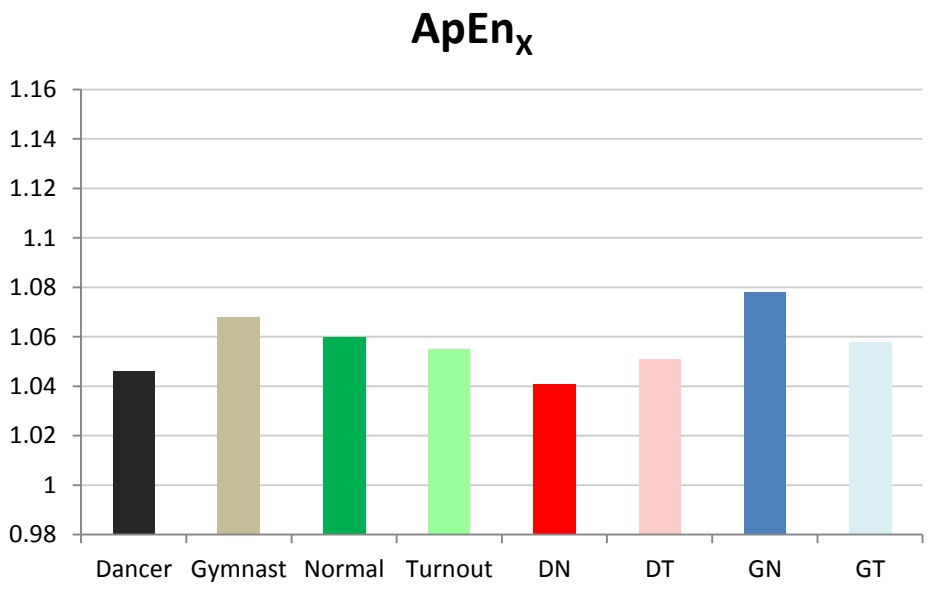


Figure 9.6: Comparisons of ApEn$_X$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

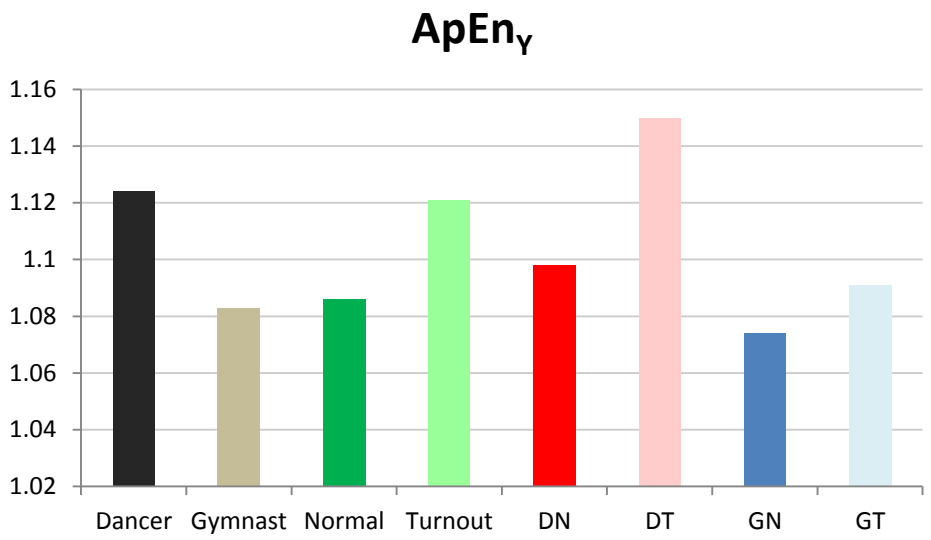


Figure 9.7: Comparisons of $ApEn_Y$ means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

9.7. DFA

DFA_X means of groups between Foot positions was significantly different but not within groups (Table 9.7 & Figure 9.8). The mean value of α from Normal foot position (0.995) was significantly smaller than from Turnout foot position (1.055). Normal foot α value indicates 'Correlated' balance data as the value is in a range between 0.5 and 1. Turnout position α value is in a range of 'Non-stationary (Unbounded, α > 1) but it might be considered as 'Pink noise' as the α value is close to 1 (Pink noise, α =1). Overall, all α values are almost equal to 1 but slightly higher or less.

There was no significant difference in comparisons of DFA_Y (Table 9.8 & Figure 9.9). All α values are in a range of 'Non-stationary' correlation. Comparing quiet balance between similar conditions (only foot was pointing in different directions) and well trained balancers (just standing on single leg without being challenged is too easy for both Groups) might not indicate different correlations in comparisons. Therefore, it is expected to have various ranges of correlations between DFA comparisons if the experiment was comparing totally different skilled groups (e.g. Basketball players vs Dancers) or comparing to more challenging standing positions (e.g. Standing on Demi-pointe or Pointe).

Table 9.7: Means and SE (Standard Error) of DFA (Sig. < 0.05)

DFA_X (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	1.001	0.326
			SE	0.033	
		Gymnast	Mean	1.049	
			SE	0.033	
	Foot positions	Normal	Mean	0.995	**0.023***
			SE	0.024	
		Turnout	Mean	1.055	
			SE	0.027	
Paired T Test	**Dancer Group**	Normal	Mean	0.979	0.283
			SE	0.020	
		Turnout	Mean	1.024	
			SE	0.027	
Paired T Test	**Gymnast Group**	Normal	Mean	1.011	0.095
			SE	0.045	
		Turnout	Mean	1.086	
			SE	0.047	
DFA_Y (mm)					Sig.
Two-way ANOVA	**Groups**	Dancer	Mean	1.114	0.877
			SE	0.044	
		Gymnast	Mean	1.104	
			SE	0.044	
	Foot positions	Normal	Mean	1.161	0.090
			SE	0.053	
		Turnout	Mean	1.056	
			SE	0.029	
Paired T Test	**Dancer Group**	Normal	Mean	1.201	0.664
			SE	0.098	
		Turnout	Mean	1.026	
			SE	0.035	

Paired T Test	**Gymnast Group**	Normal	Mean	1.121	0.357
			SE	0.038	
		Turnout	Mean	1.086	
			SE	0.047	

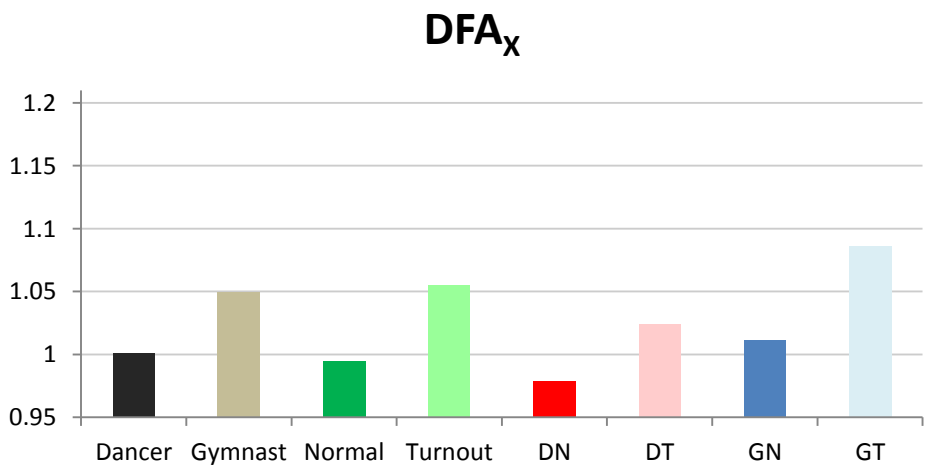


Figure 9.8: Comparisons of DFA_X means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

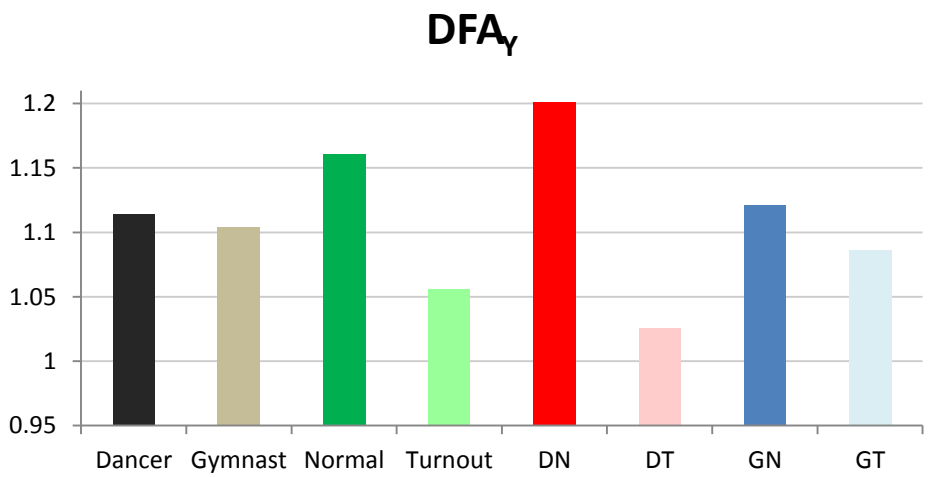


Figure 9.9: Comparisons of DFA_Y means (mm) [DN: Dancer group × Normal foot, DT: Dancer group × Turnout foot, GN: Gymnast group × Normal foot and GT: Gymnast group × Turnout foot] (Sig. < 0.05)

9.8. Discussions

The related questions are:

- Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

- Q6. What are the differences in balance control between Dancers and Gymnasts?

9.8.1. Dancer group vs Gymnast group (Q6)

During static single leg standing, gymnasts may have a larger boundary with larger sized deviation of COP than dancers to control balance. This study does not show any significant differences between groups (combined foot positions) from single leg balance but SD and Range in both AP and ML indicate that gymnasts may always have slightly larger balance corrections than dancers. According to Vuillerme et al. (2001), gymnasts can use a more sensitive sensory systems in more efficient ways compared to other elite players. Also, this research found that gymnasts perform larger range of COP on single leg standing. Perrin et al. (2002) mentioned that ballet dancers try to perform more regulated balance control developed by their training whereas judoists try to perform stable balance in any situations and circumstances. It was found from this research that judoists can maintain their balance more stably than dancers and control group. There is no research which directly compared COP during single leg balance between dancers and gymnasts as well as other groups. However, it can be discussed that each group may have developed their balance skills depending on their training, for example, how much balance sway, movement, correction are needed in the sport or situation.

In contrast, mean Sway Path from Dancer group is longer than from Gymnast group (Dancers: 3524.76 > Gymnasts: 3396.25, non-significant) even though Dancer group has smaller Range and SD. This means that dancers may continuously and more frequently move COP to control balance within smaller area compared to gymnasts. Dancers may work hard to maintain balance and keep trying to place COP around their perfect centre to stand stable longitudinal axis as this is how it is required in

dance for aesthetic purposes. There were no significant differences from ApEn but Dancer group has more predictable ApEn mean than Gymnast Group in ML but Gymnasts group is more predictable than Dancers in AP. It can be seen from this finding that each group may have its strength balance control plane compared to the other group.

It is difficult to compare balance skills among all high balance level elite groups but results from this Chapter 9 explains that each group has very developed balance skills and own inherent balance methods have been trained by required performance in each sport.

9.8.2. Normal foot position vs Turnout foot position (Q4)

COP excursion area can be varied depending on foot type and alignment of rearfoot and forefoot (varus & valgus) may also influence balance (Hertel, et al., 2002). This may give rise to some thought that changing the degree of foot position may also influence on COP area too. From Chapter 9, Turnout foot position has significantly larger SD and Range in ML than Normal foot position from each group as well as the comparison of combined group. Oppositely, Normal foot position has significantly larger SD and Range in AP from the combined group comparison. These findings indicate that Turnout foot position can create larger area to control COP in ML compared to Normal foot position but Normal position has larger COP control area in AP compared to Turnout foot. This may have been affected by foot positions and if the area is larger (e.g. Turnout > Normal in ML, Normal > Turnout in AP), COP can be also controlled within a larger area where the foot is pointed.

In Dancer group, a significant difference was found between Normal and Turnout foot position ($p=0.025$, Normal: 34.85 > Turnout: 30.62) from Range in AP. Moreover, a similar result was found from Dancer group's SD in AP that Normal foot was larger than Turnout foot position ($p=0.051$, Normal: 6.09 > Turnout: 5.27). Dancer group's SD and Range of Normal position were slightly larger compared to Gymnast group's. Simmons (2005a) found that dancers may become less stable in AP compared to controls if somatosensory feedback is not reliable. Linking to this Simmons's finding, the result from Chapter 9 also shows that dancers may not have

stable balance skills in AP direction compared to other general groups and even gymnasts. This might be because dancers get used to standing on single leg in Turnout position than Normal foot so dancers may have larger area to control COP in AP. Also dancers may have smaller area to control COP in ML compared to gymnasts and other populations. This means that dancers may have to increase COP control area in AP to compensate more controlled (reduced area) balance in ML. It was discussed in Chapter 7 that dancers may have strong TA muscle to control balance. TA helps the ankle joint to perform dorsiflexion by bringing the shank towards the forefoot rather than rear foot and it may try to move COP more in sagittal plane (AP). This may be the reason why dancers possibly have larger area to control balance in AP during Normal foot single leg stance and Turn out position in ML increases area to control balance in ML (when the foot is turned out the toe is pointing in lateral direction) and definitely larger than in AP.

Sway Path does not show any significant differences but Turnout position was longer than Normal in all comparisons from the combined groups and each separated group. This might be caused because human balance in Turnout position needs to be controlled with small and frequent corrections whereas Normal foot position probably implements larger sized corrections but less frequently.

ApEn In ML direction, Turnout position has a slightly more predictable mean value than Normal from the combination group comparison as well as from Gymnasts group, but Dancer group's Normal position is slightly more predictable than Turnout. This explains that dancers may have a more complicated ways to balance on Turnout foot in ML direction. Oppositely, Normal foot position has significantly more predictable ApEn than Turnout in AP from combined group comparison and Dancer group. Therefore, this finding also supports that dancers may also have more complex balance control in AP direction as well as in ML during Turnout single leg standing balance. Dancers may have developed their unique and sensitive ways of controlling balance during their training in Turnout foot position.

DFA in ML explains that Normal and Turnout foot position have significantly different α values and each foot position has its characteristic self-affinity such as 'Correlated

(persistence)' and 'Non-stationary (unbounded random walk)' respectively. This result indicates that single leg standing balance control can be really different depending on the foot positions. Similar to the finding from ApEn, changes of COP trajectory under Normal foot positon could be quite predictable and expectable but Turnout position has more various methods to balance and it results in having more random COP trajectories while balancing from ML direction.

9.8.3. Single vs Double (Q4)

To discuss about differences between Single leg quiet standing balance and Double leg quiet standing balance, results from Chapter 4 and Chapter 9 are reviewed. As Single leg stance is more unstable than Double leg stance, all conditions of Single leg had larger SD than all conditions of Double leg stance in both ML and AP. Also, Range of Single is larger compared to Double leg stance (Double Flat about 23 mm / Single Turnout from 30.62 mm - 31.61 mm) in AP. From Range in ML, Single is larger by comparing the flat positions) but Toe-Pointe from double leg standing is larger than single flat leg standing. Toe-Pointe (31.97 mm) and Gymnasts' Turnout (30.21 mm) have quite similar Range values in ML. Therefore, Single leg balance cause larger area to control COP compared to Double leg standing balance.

Oppositely, Single leg standing balance has shorter Sway Path compared to Double leg standing during 30 sec (e.g. Double leg Ballet shoes Flat: 4587 > Single leg Turnout from Dancer groups: 3477.88 mm). The values from two studies couldn't be compared directly to get levels of significance as these studies did not have the same subjects. However, it shows that the length of Sway Path is surely related with the size of BOS. From Chapter 4 (standing on Double legs), it was found that standing on Toe-Pointe (4399 mm) results in shorter Sway Path than other Flat (Ballet shoes: 4587 mm / Pointe shoes: 4568 mm) and Demi-pointe (Ballet shoes: 4815 mm / Pointe shoes: 4803 mm) positions. Even though Toe-Pointe position was the hardest position to control balance amongst all the conditions in Chapter 4, Sway Path was the shortest. This finding can be applied with including the results from this Chapter 9 that Sway Path can be shorter in Single leg balance than Double leg balance due to smaller BOS.

Unexpectedly, ApEn results from Chapters 4 and 9 indicate that single balance might be more predictable than double leg balance (e.g. ApEn in ML: Ballet Double leg Flat - 1.381 > Dancer Turnout - 1.051 / ApEn in AP: Ballet Double leg Flat - 1.331 > Dancer Turnout - 1.098). Balancing on both legs means that there are more feedbacks from more numbers of somatosensory receptors compared to standing on only single leg. Therefore, having more information creates various ways to balance and it may results to perform more complex structure of balance control.

CHAPTER 10

DISCUSSION AND CONCLUSION

The research purpose of this thesis was to develop an understanding of dance balance characteristics in various dance balance conditions as well as to understand different balance control systems in two different groups (Dancers vs Gymnasts). Three separated studies were designed, processed and analysed for this purpose and six research questions were posed.

Q1. What differences in balance performance are there in different ballet positions and shoe types using multiple balance metrics?

This research question could be answered from the 1st study: Ballet 2nd position in static conditions. Ballet 2nd position is standing with feet turned out on both legs. Dancers generally sway more in the Anterior-Posterior (AP) direction than in the Medial-Lateral (ML) direction during Flat & Demi-pointe feet positions but not during Toe-Pointe condition (Figure 10.1).

Dancers compensate their balance strategies by swaying more in the ML direction when on Toes with Pointe shoes. In the ML direction, Toe-Pointe condition has the largest Range, SD of COP amongst all five conditions, but has the smallest Range, SD and ApEn values in the AP direction compared to other conditions. Moreover, Sway Path of Toe-Pointe is the shortest among all conditions, which means Dancers sway less on Toe-Pointe, but ApEn values show that COP of Toe-Pointe has more repeated pattern (predictable) compared to other conditions. It can be explained that Demi-Pointe feet position has the most unpredictable balance strategy from ApEn values from both directions and this finding can be supported by high SD (in both AP & ML) and Range (in AP only). Also it can be explained why Demi-pointe feet conditions have significantly different correlations of balance (DFA) than other conditions in the AP direction. This seems to happen because:

1) Standing on Demi-Pointe allows dancers to pivot their body around the metatarsal joints to be balanced in both AP and ML direction

2) The range of ankle joints movement increases in 3 directions (AP, ML and vertical). These two reasons can support the reason why Dancers' Sway Path from Demi-pointe positions is the longest among all feet positions and significantly different to Flat.

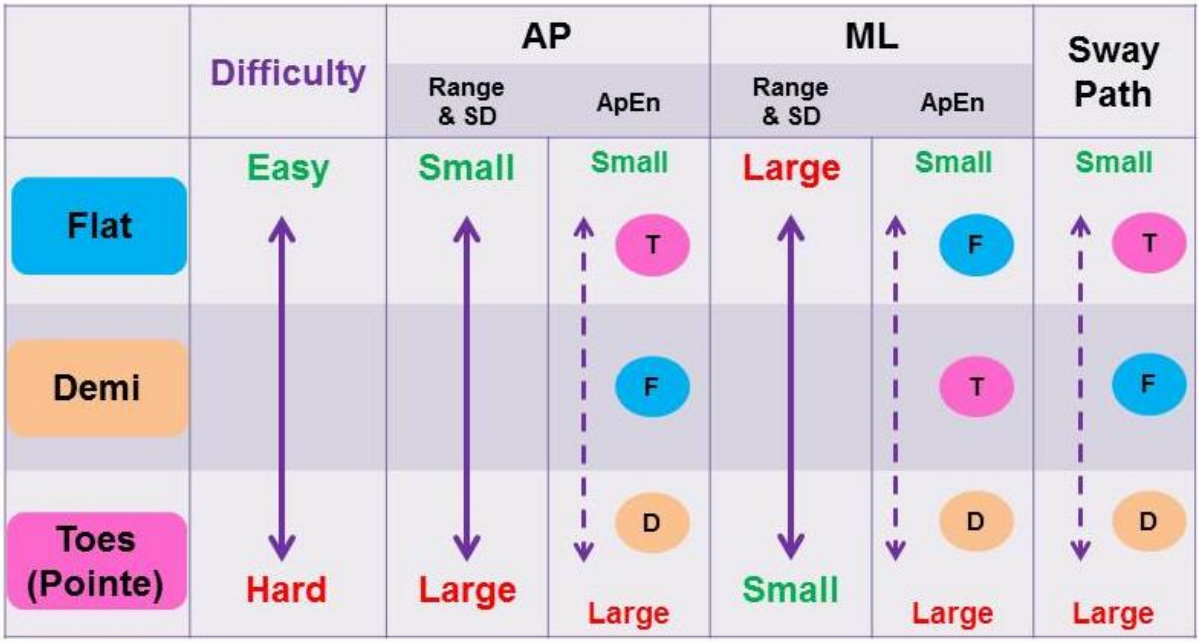


Figure 10.1: A diagram of results from the 1st study (Ballet 2nd position in static conditions) depending on multiple balance metrics

To conclude, using multiple balance metrics helps to distinguish different balance control strategies in various ballet position and it is required to develop relevant balance skills for each ballet position to be able to perform expert balance skills during dance.

Q2. What are the main characteristics of balancing on pointe shoes and do types of shoes affect balance?

This research question can be answered from the 1st study only. The two types of shoes (Ballet shoes and Pointe shoes) do not provide significantly different effects for the same feet position. However, different foot positions give significantly different effect on balance control and there are many findings from the 1st study to support this.

Some characteristics of balancing on Toe-Pointe have been explained previously in the discussion & conclusion of Q1. Additionally, several reasons why 'Toe-Pointe shoes' condition changes Dancers' balance control can be inferred:

1) Base Of Support (BOS) in AP direction gets smaller on Toe-Pointe compared to Flat and Demi-pointe positions. Therefore, Dancers sway less in AP direction during Toe-Pointe than in other foot positions. Instead, Dancers increase their sway in ML direction to compensate during Toe-Pointe as standing on tip toes is challenging.

2) Dancers need to do more plantar and dorsa flexion (but they try to do more plantar flexion) during standing on Toe-Pointe than in other feet positions and it causes them to have greater values for Range and SD in the ML direction.

3) Controls of metatarsal and ankle joints in the AP direction can be restricted on Toe-Pointe compared to Flat and especially Demi-pointe feet positions because metatarsal joints are covered in the solid pointe shoes (it is possible to do up & down movements but it is not possible to move sides) when they are wearing the Pointe-shoes.

Therefore, it can be explained that Toe-Pointe condition has unique characteristics for its balance strategy. For training, it is recommended to focus on learning balance skills for one type of shoe or one type of foot position first and then move on to other type of shoe if the dancer is a beginner. For example, beginner ballet dancers need to learn balancing on Flat first then move to Demi-pointe and then Toe-Pointe while spending enough time on each condition. Especially, when learning standing on Toe-pointe, it is better to have enough time to practise standing on Toe using pointe shoes rather than mixing different conditions too often during the day. It may be

difficult for beginners to train on pointe for a long time but they can have additional supports (e.g. bar) to begin with.

Learning balance with Pointe shoes takes many years to be able to perform well so it is important to learn the new balance strategy and keep giving the same sensory information and feedback to learn balancing on Toe-Pointe as quickly as possible and to improve skills. For great performers who perform on stage, it may be better to focus on pointe before their dance show or performance to not confuse neurological sensory system.

Balancing with various feet positions with different types of shoes in ballet requires dancers to use different balance control and strategies. Understanding the different balance controls between feet positions with different types of shoes can be helpful to improve balance skills and to reduce injuries.

Q3. Are balance strategies related to dance positions (Turnout versus Normal) and/or level of difficulty (Flat feet versus Demi-Pointe)?

This research question can be answered mainly from the 2nd study and a part of the 3rd study.

[The 2nd study (Chapter 5): Balance control and response to perturbations whilst standing on both legs in dance positions using a moving platform]

The fastest EMG latencies amongst six shank EMG sensors were analysed from the 2nd study. Based on EMG latencies from double legs standing, balance strategies are differed between Flat feet and Demi-Pointe (depending on level of difficulty) and Flat position may always react quicker than Demi-Pointe position.

EMG latencies got more delayed in the harder balance control conditions (e.g. Demi-Pointe positions) than in the easier conditions (e.g. Flat positions). This is because the muscles on shanks may be already working with a small amount of activations to keep standing up right on Demi-Pointe positions even before balance is being

perturbed. Therefore, some reasons why it may take a longer time to react against stimulus (platform movement) can be inferred:
1) The CNS is sending information already to keep correcting quiet standing balance on Demi-Pointe by using closed-loop feedback system. Therefore, the person may have to stop the current balance control programme to start the new program.

2) Ankle joints movements are restricted to perform any further plantar flexion. If the top of the feet is fully extended (maximum plantar flexion), ankles may have difficulties to help balance control so other joints have to react and respond first.

The different directions to place dance feet position (Normal and Turnout feet positions) may not affect EMG latencies during Double leg standing balance. However, Turnout feet positions (especially Turnout Flat) may be easier to react to perturbations to remain balanced than Normal feet positions because of quicker EMG latencies.

[The 3rd study: Comparisons of balance control and response to perturbations in single leg standing dance positions between Dancers and Gymnasts]

The 3rd study can answer Q3 about differences in dance foot positions between Turnout and Normal only. As it has been found from the 2nd study (double legs standing), the 3rd study (single leg standing) has the same finding that the Turnout foot position may be helpful to react and respond quicker to prevent falls (external perturbation) better than the Normal foot condition.

To conclude, Turnout position may allow better changes to be made to posture to enable greater resistance to falling and responding against any applied external force during both single leg standing and double leg standing. This may be due to:
1) There are more muscles getting involved to balance depending on directions of balance perturbation by placing Turnout position. For example, PL is the main muscle to work against lateral direction of platform movement (the body falling to the medial side) during Normal foot position. However, the 2nd working muscle TA can get more involved to react quicker when the foot position is Turnout so both PL and TA muscles can work in the same direction. This can be applied to other directions

(e.g. Backward - Normal: GA, Turnout: PL & GA / Medial - Normal: TA, Turnout - TA & GA) apart from Forward platform movement (falling backward, only TA muscle gets involved as the main muscle and Turnout position depends more on TA to prevent falling than Normal position).

2) Turnout position on single leg standing allows having greater physical range of motion in certain directions compared to Normal position. COM can deviate outside of COM very easily in a situation of falling sideways (lateral & medial) while standing on single leg than on double legs. However, Turnout foot position increases BOS laterally so COP can be moved more in ML direction and this helps to keep COM in a larger area of BOS in ML. Moreover, ankle and knee joints (hip as well) may help to increase range of motion in ML.

These are the reasons why Turnout position (even slightly Turnout) has also been used in some sports or martial arts, where high levelled balance skills are required in, and some defence and attack positions are developed by using Turnout position as well as dance. Standing on Demi-Pointe may make it harder to react quicker at falling after a perturbation is applied externally because the CNS is busy to cope with current closed-loop feedback system to be able to balance on Demi-Pointe. Therefore, Turnout-Flat position would be the best for balance.

Q4. Are balance strategies different in dance positions (Turnout versus Normal) between standing on single leg and standing on double legs?

None of the studies in this thesis directly investigated differences between single leg and double legs standing in one study. However, differences or effect of foot positions on balance can be discussed by using findings from all three studies.

During quiet standing on double legs, the human body sways more in AP direction than ML direction using the ankle strategy (Winter, 1995). Double legs standing on Flat and Demi-Pointe in Turnout position (from the 1st study) and single leg standing on both Normal and Turnout foot positions (from the 3rd study) show that COP movement of the Dancers and Gymnasts is larger in AP than ML direction. The reason why the same finding was discovered with the various foot positions used in

the studies might be because of human's foot shape. Humans perform dorsiflexion and plantaflexion with the foot or feet to control balance (Winter, 1995) because foot has a long shape in AP and narrow in ML. Also, the long foot shape in AP helps occurring larger sway without the risk of placing COM outside BOS in AP. Between Normal and Turnout positions in single leg standing (from the 3rd study), Normal position may allow human to sway more (greater Range and SD of COP) in AP direction but less in ML direction compared to Turnout position. This supports the finding that human's balance will be controlled by doing dorsiflexion (using TA, to stop falling backward - Forward platform movement) & plantaflexion (using GA, to stop falling forward - Backward platform movement) of ankle. Also, COP trajectory will lie within the long shape of the foot but depending on in which direction the tip of foot is pointed. Even though the foot or feet are placed in Turnout position, the human body still may sway more in AP direction than in ML as Turnout position is not 90° turned out from Normal (parallel) position. Therefore, TA and GA muscles will still work to control balance by performing dorsiflexion & plantaflexion and will have additional help by another muscle to stop falling forward (PL, having Backward platform movement).

Quiet double legs standing may have more unpredictable COP pattern and longer Sway Path than single leg standing. These may be that the larger BOS allows human's to sway in a larger area (Sway Path) and using another leg gives extra information by using a larger number of somatosensory proprioceptive system (unpredictable).

Dancers can control their balance on Turnout single leg stance with a smaller range of COP movement in AP direction but larger range of COP in MP direction compared to balancing on Normal single leg. Sway Path of Dancers in Turnout position has the longest length amongst all the conditions. These findings may support discussions mentioned in dynamic balance control that Dancers have good balance control in Turnout position as they are already ready to recover from balance perturbations by having large amount of COP movement in Static balance condition. Dancers can perform better control of static balance by controlling their movements within the broader, safe boundaries and this is the reason why dancers are able to quickly control their balance during balance perturbations in Turnout foot position.

Understanding whole balance control system is not simple but researching into specific balance positions can be helpful to comprehend broad area of balance system in the future.

Q5. How do responses and corrections in dance positions differ depending on the directions and speed of external perturbations and are there any differences in these responses depending on the dance positions?

This research question can be found partly from Chapter 5 (the 2nd study) and mainly from Chapter 6, 7, 8 & 9 (the 3rd study).

Based on EMG latencies and Torque responses from the 3rd study, both Dancers and Gymnasts can generally react quicker to Backward and slower to Medial, Lateral and Forward platform movement in the order (Table 10.1). EMG was much quicker in Medial platform movement than in Forward movement when only directions of platform movement were considered. However, Torque is much quicker in Backward direction compared to both Forward and Lateral directions.

Table 10.1: The general orders of EMG latencies and Torque responses depending on directions of platform movement (combined foot positions)

		Platform movements		Falling directions
1	Quick	Backward	→	Falling Forward
2	↕	Medial	→	Falling Lateral
3		Lateral	→	Falling Medial
4	Slow	Forward	→	Falling Backward

Turnout foot position gives a larger BOS area in the lateral direction from the ankle joint compared to Normal foot position. Therefore, Dancers, who are trained in Turnout foot position, can control their balance quickly enough when they start falling laterally (caused by Medial direction of platform movement) during Turnout foot

position. Moreover, Dancers Turnout position might be more turned out toward to lateral direction with larger degree from the Normal foot position point compared to Gymnasts as they are highly trained to dance in Turnout foot position.

Non-parametric order tests and frequency order tests (from Chapter 7) indicate that each direction of platform movement has a muscle that reacts first. Forward-TA, Backward-GA, Lateral-PL and Medial-TA and it can be seen that the muscle placed on the same side as platform movement works first to prevent falling to the opposite direction.

In Normal foot position, TA, GA, PL and TA are the fastest muscles that react most in Forward, Backward, Lateral and Medial directions respectively from both Dancer and Gymnast groups. TA, PL and PL are the most common muscles to react first after Forward, Backward and Lateral platform movement respectively in Turnout foot position. However, GA is the first reacting muscle in Medial direction for Dancers and TA is the first reacting muscle in the same direction from Gymnasts. These finding may be caused by angle of Turnout position from Normal foot position. Dancers can produce a more Turned out foot position than Gymnasts because of their training. Training muscles around the shank in various directions will be helpful to recover balance after perturbation, not only the TA and GA. It is important to train PA muscles to have good balance control skills while falling medially (Lateral platforms movement) in Normal foot and falling forwards (Backward platform movement) in Turnout foot position.

In terms of speeds, EMG latencies do not have significant differences between speeds of platform movement. However, Torque responses indicate that the subjects generally perform quicker at Fast platform movement than at Slow platform movement.

As a quick summary from Chapter 5 based on the 2nd study, Turnout Flat feet position may be considered as the best feet position amongst four feet conditions (Normal Flat, Normal Demi-Pointe, Turnout Flat and Turnout Demi-Pointe) to react quickly in double legs balance after Forward or Backward stimuli. Differences of EMG latencies depending on directions of platform movement have not been

analysed yet and these are left for future analyses. It will be necessary to discuss effects of Directions within and between feet positions in the future. For example, Normal Flat may have shorter EMG latencies than Turnout Flat during Backward platform movement and Turnout Flat might have shorter EMG latencies than Normal Flat during Forward platform movement according to findings from the 3rd study.

Q6. What are the differences in balance control between Dancers and Gymnasts?

This research question can be answered from the results of the 3rd study. Both Dancers and Gymnasts may react and respond quicker in Turnout foot position than in Normal foot position. EMG latencies, directions and speeds of combined groups definitely indicate that the subjects react quicker during Turnout foot stance than in Normal foot with a significant difference. Torque response from this comparison and other smaller comparisons of EMG and Torque (within the groups) do not show significant differences between foot positions but all mean values support that Turnout position is quicker to react or respond for the subjects.

Overall, Dancers have lower EMG latencies in Medial than in Forward direction. Torque has quicker responses in Backward than in Medial in Dancer group but Forward direction has the longest delay amongst all four directions which is supported by the result from EMG latencies. The human body is well trained to control balance in the AP direction, falling Backward (Forward platform movement) may not be the direction that the subjects would struggle to recover balance in even if this direction has the slowest response because the plantar flexor is the strongest single limb muscle response to stop fall when COP travels to go outside of BOS. Gymnast group has the lowest EMG latencies in Backward direction and Torque responses also support the EMG results by showing significant differences in Forward and Lateral directions.

In Normal foot position, both Dancer and Gymnast groups have the quickest Torque response in Backward platform movement and the slowest responses in Forward or Lateral directions. In Turnout foot position, both groups have the slowest Torque response in Forward direction and the order from the slowest to fastest is ‘Forward >

Lateral > Medial > Backward'. However, only the fastest Torque responses amongst all torques from Dancer group have an alternate order between Medial and Backward directions. It can be considered from these findings that Forward platform movement, and hence backward falling, is the hardest condition to recover balance in. Backward platform movement is generally the quickest for the subjects to respond but Medial direction can be the quickest for Dancers when they are balancing on Turnout foot as their foot is pointing laterally. Turnout foot in Medial direction can be similar to Normal foot in Backward direction. Torque response of Dancer in Turnout Medial direction is the quickest amongst all eight directions with separated foot positions which means they are particularly well trained to control their balance in Turnout foot Medial direction. Gymnasts' Torque responses of Directions are more variable than Dancers and they are probably less restricted to control balance than Dancers in Forward and Lateral direction. During Normal foot position, Lateral direction of platform movement might be the slowest Torque responses and most of the balance recovery failures happened in the Lateral direction. This might be affected by a smaller size of BOS in ML direction compared to AP direction.

The Dancer group is particularly skilled to react and respond quicker than the Gymnast group in Turnout position at Slow Forward platform movement. As it has been discussed before, Forward platform movement can be the slowest direction to recover balance but Dancers are trained to balance stably in Turnout position and Slow platform movement is probably a similar balance perturbation environment to what Dancers normally need to handle in Dance training. Also, balance recovery from falling backward (e.g. when Slow Forward platform movement happens) in Turnout may be enhanced by using TA, which has been trained from dance environment, from dancers.

Comparisons of Torques in each condition between Dancer and Gymnast groups indicate that if there was any significant differences found between the groups, Dancer group generally has the quicker Torque responses than Gymnasts around the main rotation axis of Ankle depending on the Directions of platform movement (only Turnout Fast has the quicker response than Gymnasts around $Knee_X$). However, Gymnast group has the quicker Torque responses than Dancers around

the main rotation axes of Knee and Hip and even around non-main axes. These findings can support that Gymnasts have variable balance control by creating their Knee and Hip joints Torques quicker than Dancers. However, Dancers are probably better at using Ankle strategy first than Gymnasts.

Non-parametric test (Chapter 7) indicates differences in balance control between Dancers and Gymnasts. GA is the first reacting muscle in Medial direction for Dancers and TA is the first reacting muscle in the same direction from Gymnasts. These finding may be caused by angle of Turnout position from Normal foot position. Dancers can produce a more Turned out foot position than Gymnasts because of their training.

To conclude, performing quick reactions and responses can mean that the body can recover their balance after being perturbed. Human can react and respond more quickly after Backward platform movement (falling forward) than for other directions of platform movement. Therefore, trying to keep balance slightly forward in Turnout foot position can be a safe way to balance to avoid a fall when balance is disturbed from any direction. Dancers are more skilled to recover balance than Gymnasts in Turnout position but balance control of Gymnasts can be more varied than Dancers depending on the directions of platform movement especially in Turnout position.

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APPENDIX 1

Informed Consent Forms

Appendix 1.1- Informed Consent Form for the first study

Loughborough University

Investigating into balance control and response in dance: 1st part, a balance study into ballet 2nd position between 2 types of shoe (Ballet and Pointe shoes)

INFORMED CONSENT FORM
(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name _____

Your signature _____

Signature of investigator _____

Date _____

Appendix 1.2- Informed Consent Form for the 2ND and 3rd studies

Loughborough University

Investigation into balance, control and response during standing positions

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethics Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name _____

Your signature _____

Signature of investigator _____

Date _____

APPENDIX 2

Subject information Sheets

Appendix 2.1- Subject Information Sheet for the 1st study

Loughborough University

Investigating into balance control and response in dance: 1st part, a balance study into ballet 2nd position between 2 types of shoe (Ballet and Pointe shoes)

Participant Information Sheet

Investigator Contact Details

Ravina Huh (Eunhye Huh) - UU.1.15 - E.Huh@lboro.ac.uk

Dr Matthew Pain - UU.1.07 - M.T.G.Pain@lboro.ac.uk

What is the purpose of the study?

The aim of this research is to examine how ballet 2nd position balance is affected by different shoes and conditions depending on 2 types of shoe (ballet shoes and pointe shoes). Also, this research will assess how balance can be different between ballet and pointe shoes. The result of this research will help dancers to understand differences and their training.

Who is doing this research and why?

This study is part of a PhD research project examining balance skills in various ballet 2nd positions with 2 types of shoe and this research project is conducted by the sports biomechanics and motor control research group.

Are there any exclusion criteria?

To measure reliable balance, generally the duration of around 30 sec is required in many researches. Therefore, all participants are required to perform ballet 2nd position for 30 sec on toes and tip-toes (only with pointe shoes). Therefore, participants should be able to stand on toes and tip-toes for 30 sec and anyone who has a current injury to their lower limbs and hip should not take this test.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

How long will it take?

This research will take only for one hour in total (Approximately, attaching Makers: 15 min, total break times: 10 min, performing 5 conditions of ballet second balance: 35min).

What type of clothing should I wear?

Reflective motion markers will be attached on the skin, therefore short and tight clothes will be required for this test to get accurate data. Own ballet and pointe shoes (pads as well) will be required.

What will I be asked to do?

Participants will be required to attend only one testing session which has 5 conditions of ballet 2nd positions (ballet shoes: flat foot, demi-pointe/ pointe shoes: flat foot, demi-pointe, toe-standing). Each condition should be performed for 30 sec 6 times to assess static balance. During these sessions reflective markers will be placed on the skin to measure the body posture and a participant will perform ballet balance on two force plates to measure forces generated by the body.

Are there any risks in participating?

As a static balance study, there is no big risk participating. However, if the participant has not trained ballet with pointe shoes for a period, it might be harmful to feet.

Will my taking part in this study be kept confidential?

All data collected in this research will remain secure. Participant will not be referred to by name outside of data collections such as publication of the study.

What will happen to the results of the study?

All data collected conform to the university's guidelines on data collection and storage. Therefore, data will be stored securely in its original state for the duration of the collections, analysis and publication of the study.

What do I get for participating?

Firstly, a brief opinion of your test will be sent individually such as body posture, position. After analysing, all results and facts will be messaged again and scientific ballet information will be shared.

I have some more questions who should I contact?

Any questions regarding the test or ballet balance practice should be first addressed to Ravina Huh (E.Huh@lboro.ac.uk). Alternatively, further queries may be addressed to Dr Matthew Pain listed above.

If you have any concerns regarding your participation in this study, or the conduct of any of the investigators involved, the University has a policy relating to Research Misconduct and Whistle Blowing which is available online

at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Appendix 2.3- Subject Information Sheet for the 2nd and 3rd studies

Investigation into balance, control and response during standing positions

Investigator Contact Details

Ravina Huh (Eunhye Huh) - UU.1.15 - E.Huh@lboro.ac.uk

Dr Matthew Pain - UU.1.07 - M.T.G.Pain@lboro.ac.uk

What is the purpose of the study?

The aim of this research is to examine how human balance is controlled depending on directions, velocities and amplitudes of a moving platform. Also, this research will assess how balance can be different depending on foot or feet positions. The result of this research will help gymnasts and dancers to understand differences and their training.

Who is doing this research and why?

This study is a part of Eunhye Huh's PhD research projects supported by Loughborough University and will exam balance skills in various standing conditions (standing normal and turned out legs) with 2 types of feet positions (flat and demi-pointe) and this research project is conducted by the sports biomechanics and motor control research group.

Are there any exclusion criteria?

Anyone who has a current injury to their lower limbs and hip should not take this test.

What will I be asked to do?

To measure balance, control and response you will be asked to perform 4 types of one leg standing position on a force plate (standing normal with flat foot, standing normal on toes, turned bout leg with flat foot and turned out leg on toes). During these sessions markers will be placed on your skin to measure the movement. When you keep your balance on the force plate, the platform will move in one of 4 directions (forward, backward, left and right). Therefore, you need to try to keep your balance while the platform is moving. This experiment has TWO sessions.

At the first testing session, you will be asked to stand on a force plate for 30 seconds (flat foot positions) or as long as you can (standing on toes positions). Each type of standing position has 6 trials so all participants need to complete 24 trials.

At the second testing session, you will be asked to stand on a force plate but the platform will move after a few seconds. There are 4 directions of platform movement (forward, backward, left and right) and each direction has 2 different moving speeds (fast and slow). You only needs to perform flat foot positions (standing normal with flat foot and turned out leg with flat foot) NOT toe standing. Therefore, you will complete 48 trials short.

Once I take part, can I change my mind?

Yes! After you have read this information and asked any questions you may have we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact one of the investigators. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing.

Will I be required to attend any sessions and where will these be?

All participants will complete 2 sessions (same day) in Wavy top (L0.11).

How long will it take?

This research will take approximately for 1 hour and 30 mins in total (measuring length of body segments: 10 min, attaching markers: 20 min, total break times: 10 min, session 1: 25 min, session 2: 25 min).

What personal information will be required from me?

Participants' weight, height, segment lengths will be measured but this information will not be shared.

Are there any risks in participating?

There is no big risk participating.

Will my taking part in this study be kept confidential?

All data collected in this research will remain secure. Participant will not be referred to by name outside of data collections such as publication of the study.

I have some more questions; who should I contact?

Any questions regarding the test should be first addressed to Eunhye (Ravina) Huh (E.Huh@lboro.ac.uk). Alternatively, further queries may be addressed to Dr Matthew Pain listed above.

What will happen to the results of the study?

All data collected conform to the university's guidelines on data collection and storage. Therefore, data will be stored securely in its original state for the duration of the collections, analysis and publication of the study.

What if I am not happy with how the research was conducted?

If you are not happy with how the research was conducted, please contact Mrs Zoe Stockdale, the Secretary for the University's Ethics Approvals (Human Participants) Sub-Committee:

Mrs Z Stockdale, Research Office, Rutland Building, Loughborough University, Epinal Way, Loughborough, LE11 3TU. Tel: 01509 222423. Email: Z.C.Stockdale@lboro.ac.uk

The University also has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Is there anything I need to do before the sessions?

New types of hard physical training are not recommended from a day or two before.

Is there anything I need to bring with me?

Own water and snacks, if it is needed.

What type of clothing should I wear?

Reflective motion markers and EMG markers will be attached on the skin, therefore short and tight clothes (sleeveless) with not retro-reflective strips will be required for this test to get accurate data.

Who should I send the questionnaire back to?

The completed questionnaire should be handed to Eunhye (Ravina) Huh (E.Huh@lboro.ac.uk).

What do I get for participating?

Brief information of your test will be sent individually such as body posture, position, segment length and weight. After analysing, all results and facts will be messaged again and scientific dance information will be shared.

APPENDIX 3

Matlab Codes

Appendix 3.2 - Matlab code for analysing Static balance data

```
clear
tic
for f=1:7;
    try
    if f<10, number=['0',num2str(f)];
    else number=num2str(f);
    end
    file=['Pointe_Toe_',number];

name='Alanah_';
fend='.csv';
dir='C:\Users\pseh\Personal Documents - Not Backed Up\personal
research\RavinaHuh\Ballet 2nd balance\Alanah\Session 1\';
A=importdata([dir,file,fend],',',66027);

toc
'file'
 for DD=1:size(A.data,2);
     Data(:,DD)=decimate(A.data(:,DD),10,4,'fir');
 end
Ax1=Data(:,2);
Ay1=Data(:,3);
Ax2=Data(:,14);
Ay2=Data(:,15);
Fz1=Data(:,10);
Fz2=Data(:,22);
COPx1=Data(:,2);
COPy1=Data(:,3);
COPx2=Data(:,14);
COPy2=Data(:,15);
Fx1=Data(:,8);
Fx2=Data(:,20);
Fy1=Data(:,9);
Fy2=Data(:,21);
Fx=(Fx1+Fx2);
Fy=(Fy1+Fy2);
Fz=(Fz1+Fz2);
COPx=((Ax1.*Fz1)+(Ax2.*Fz2))./(Fz1+Fz2);
COPy=((Ay1.*Fz1)+(Ay2.*Fz2))./(Fz1+Fz2);
xlswrite([name,file],COPx,1,'A')
xlswrite([name,file],COPy,1,'B')
xlswrite([name,file],Fx,1,'D')
xlswrite([name,file],Fy,1,'E')
xlswrite([name,file],Fz,1,'F')
Mx=(Data(:,11)+Data(:,23));
My=(Data(:,12)+Data(:,24));
Mz=(Data(:,13)+Data(:,25));
xlswrite([name,file],Mx,1,'H')
xlswrite([name,file],My,1,'I')
% From here, this funtion is for 'Swaypath'
X(:,1)=COPx;
X(:,2)=COPy;
Hz=200;
W=30;
SP_Ans=Swaypath(X,Hz,W);
toc
'functions'
xlswrite([name,file],SP_Ans,2,'A')
toc
```

```
'write 1'

% From here, this is a funtion of 'DE trended Fluctuation Analysis' for
% COPx
N=3.*Hz;
DFA_COPx_Ans=DFA(COPx,Hz,N);
xlswrite([name,file],DFA_COPx_Ans,3,'A')
toc
'write 2'
% COPy
DFA_COPy_Ans=DFA(COPy,Hz,N);
xlswrite([name,file],DFA_COPy_Ans,3,'D')
toc
'write 3'

% Surrogate COPx
Sur_COPx_Ans=Surrogate(COPx);

% Surrogate COPy
Sur_COPy_Ans=Surrogate(COPy);

% From here, this is calling 'Approximate Entropy COPx'
% Instead of writing 'data' use COPx value
M=2;
R=0.2;
AE_COPx_Ans(1)=ApEn(Sur_COPx_Ans(:,1),M,R);
AE_COPx_Ans(2)=ApEn(Sur_COPx_Ans(:,2),M,R);
xlswrite([name,file],Sur_COPx_Ans,4,'A')
xlswrite([name,file],AE_COPx_Ans(1),4,'D')
xlswrite([name,file],AE_COPx_Ans(2),4,'E')
toc
'write 4'

% COPy value

AE_COPy_Ans(1)=ApEn(Sur_COPy_Ans(:,1),M,R);
AE_COPy_Ans(2)=ApEn(Sur_COPy_Ans(:,2),M,R);
xlswrite([name,file],Sur_COPy_Ans,4,'H')
xlswrite([name,file],AE_COPy_Ans(1),4,'K')
xlswrite([name,file],AE_COPy_Ans(2),4,'L')
toc
'write 5'

out=psd([COPx,COPy],200,[0.05,0.95],5);
xlswrite([name,file],psd([COPx,COPy],200,[0.05,0.95],5),5,'A')


    catch
    end

end
```

Appendix 3.2 - Matlab code for EMG data

```
clear

    EMG_TITLE=[{'R Abs'},{'L Abs'},{'R Lumber'},{'L Lumber'},{'R
Glutus'},{'L Glutus'},{'R R Femoris'},{'L R Femoris'},{'R Ham'},{'L
Ham'},{'R Tibialis'},{'L Tibialis'},{'R Peroneus'},{'L Peroneus'},{'R
Gastro'},{'L Gastro'}];

    Marker_TITLE=[{'Field
#'},{'Head_F_RightX'},{'Head_F_RightY'},{'Head_F_RightZ'},{'Head_F_LeftX'},
{'Head_F_LeftY'},{'Head_F_LeftZ'},{'Head_B_RightX'},{'Head_B_RightY'},{'Hea
d_B_RightZ'},{'Head_B_LeftX'},{'Head_B_LeftY'},{'Head_B_LeftZ'},{'SternumX'
},{'SternumY'},{'SternumZ'},{'XiphoidX'},{'XiphoidY'},{'XiphoidZ'},{'C7X'},
{'C7Y'},{'C7Z'},{'T10X'},{'T10Y'},{'T10Z'},{'L1X'},{'L1Y'},{'L1Z'},{'R_Scap
ulaX'},{'R_ScapulaY'},{'R_ScapulaZ'},{'Right_Anterior_ShoulderX'},{'Right_A
nterior_ShoulderY'},{'Right_Anterior_ShoulderZ'},{'Right_AcromionX'},{'Righ
t_AcromionY'},{'Right_AcromionZ'},{'Right_Posterior_ShoulderX'},{'Right_Pos
terior_ShoulderY'},{'Right_Posterior_ShoulderZ'},{'Right_LEX'},{'Right_LEY'
},{'Right_LEZ'},{'Right_MEX'},{'Right_MEY'},{'Right_MEZ'},{'Right_LWX'},{'R
ight_LWY'},{'Right_LWZ'},{'Right_MWX'},{'Right_MWY'},{'Right_MWZ'},{'Right_
3MPX'},{'Right_3MPY'},{'Right_3MPZ'},{'Left_Anterior_ShoulderX'},{'Left_Ant
erior_ShoulderY'},{'Left_Anterior_ShoulderZ'},{'Left_AcromionX'},{'Left_Acr
omionY'},{'Left_AcromionZ'},{'Left_Posterior_ShoulderX'},{'Left_Posterior_S
houlderY'},{'Left_Posterior_ShoulderZ'},{'Left_LEX'},{'Left_LEY'},{'Left_LE
Z'},{'Left_MEX'},{'Left_MEY'},{'Left_MEZ'},{'Left_LWX'},{'Left_LWY'},{'Left
_LWZ'},{'Left_MWX'},{'Left_MWY'},{'Left_MWZ'},{'Left_3MPX'},{'Left_3MPY'},{
'Left_3MPZ'},{'Right_ASISX'},{'Right_ASISY'},{'Right_ASISZ'},{'Left_ASISX'}
,{'Left_ASISY'},{'Left_ASISZ'},{'Right_PSISX'},{'Right_PSISY'},{'Right_PSIS
Z'},{'Left_PSISX'},{'Left_PSISY'},{'Left_PSISZ'},{'Right_HipX'},{'Right_Hip
Y'},{'Right_HipZ'},{'Left_HipX'},{'Left_HipY'},{'Left_HipZ'},{'L_HipX'},{'L
_HipY'},{'L_HipZ'},{'Right_LKX'},{'Right_LKY'},{'Right_LKZ'},{'Right_MKX'},
{'Right_MKY'},{'Right_MKZ'},{'Left_LKX'},{'Left_LKY'},{'Left_LKZ'},{'Left_M
KX'},{'Left_MKY'},{'Left_MKZ'},{'Right_LAX'},{'Right_LAY'},{'Right_LAZ'},{'
Right_MAX'},{'Right_MAY'},{'Right_MAZ'},{'Right_HeelX'},{'Right_HeelY'},{'R
ight_HeelZ'},{'Right_5MPTX'},{'Right_5MPTY'},{'Right_5MPTZ'},{'Right_1MPTX'
},{'Right_1MPTY'},{'Right_1MPTZ'},{'Right_ToeX'},{'Right_ToeY'},{'Right_Toe
Z'},{'Left_LAX'},{'Left_LAY'},{'Left_LAZ'},{'Left_MAX'},{'Left_MAY'},{'Left
_MAZ'},{'Left_HeelX'},{'Left_HeelY'},{'Left_HeelZ'},{'Left_5MPTX'},{'Left_5
MPTY'},{'Left_5MPTZ'},{'Left_1MPTX'},{'Left_1MPTY'},{'Left_1MPTZ'},{'Left_T
oeX'},{'Left_ToeY'},{'Left_ToeZ'},{'Screen_RightX'},{'Screen_RightY'},{'Scr
een_RightZ'},{'Screen_LeftX'},{'Screen_LeftY'},{'Screen_LeftZ'},{'Wall_Righ
tX'},{'Wall_RightY'},{'Wall_RightZ'},{'Wall_LeftX'},{'Wall_LeftY'},{'Wall_L
eftZ'},{'FPCX'},{'FPCY'},{'FPCZ'},{'LANKLEX'},{'LANKLEY'},{'LANKLEZ'},{'LHJ
CX'},{'LHJCY'},{'LHJCZ'},{'LKNEEX'},{'LKNEEY'},{'LKNEEZ'},{'LMPTX'},{'LMPTY
'},{'LMPTZ'},{'L_iliacX'},{'L_iliacY'},{'L_iliacZ'},{'PELX'},{'PELY'},{'PEL
Z'},{'RANKLEX'},{'RANKLEY'},{'RANKLEZ'},{'RHJCX'},{'RHJCY'},{'RHJCZ'},{'RKN
EEX'},{'RKNEEY'},{'RKNEEZ'},{'RMPTX'},{'RMPTY'},{'RMPTZ'},{'R_iliacX'},{'R_
iliacY'},{'R_iliacZ'},{'SacrumX'},{'SacrumY'},{'SacrumZ'}];
tic
%%plot_data=1;    %1=plot, 0=don't plot
for f=1:18;
    try
    if f<10, number=['0',num2str(f)];
    else number=num2str(f);
    end
    file=['F:\Personal Documents - Not Backed Up\personal
research\RavinaHuh\Moving platform 1\Hannah\Session
1\Ballet_Demi_2nd_',number,'.csv']; %% This allows you to run one block (16
trials but can be 1 or 2 more)
                                        %% Every single subject has
```

```
    name='Ballet_Demi_2nd_';
    fend='.csv';
    dir='F:\Personal Documents - Not Backed Up\personal
research\RavinaHuh\Moving platform 1\Hannah\Session 1';
toc

    [a,b,c]=importdata(file,',');
    if isempty(a.data)==0

    Mdata=a.data;
    Mlabels=a.colheaders;

    [a,b,c]=importdata(file,',',size(a.data,1)+c+5);
    Adata=a.data;
    Alabels=a.colheaders;

    [a,b,c]=importdata(file,',',size(a.data,1)+c+11);
    Fdata=a.data;
    Flabels=a.colheaders;

    %% Should add force data from 2 force plates to recognise the
directions of platform movement
   Fx=Fdata(:,8)+Fdata(:,20); %% Use it for 'Right' and 'Left' directions
   Fy=Fdata(:,9)+Fdata(:,21); %% Use it for 'Forward' and 'Backward'
directions

   Original_EMG=Adata(:,14:31); %% To rewrite EMG data from the first
column (easier to regonise which one is what for?)
   EMG=abs(Original_EMG(:,1:18)); %% Get absolute values first! will be
overwrited later
   A_EMG=abs(Original_EMG(:,1:18)); %%Later, use this file to add right and
left together
   %% Add the same muscles' activities together (Right + Left)for AP
perturbation
   Abs=(A_EMG(:,1))+(A_EMG(:,2));
   Lumber=(A_EMG(:,3))+(A_EMG(:,4));
   Glutus=(A_EMG(:,5))+(A_EMG(:,6));
   R_Femoris=(A_EMG(:,7))+(A_EMG(:,8));
   Ham=(A_EMG(:,9))+(A_EMG(:,10));
   Tibialis=(A_EMG(:,11))+(A_EMG(:,12));
   Peroneus=(A_EMG(:,13))+(A_EMG(:,14));
   Gastro=(A_EMG(:,15))+(A_EMG(:,16));

   %% Add the same sides of muscles' activities together (Front+Back) for
side perturbation
   R_Abs_Lumber=(A_EMG(:,1))+(A_EMG(:,3));
   L_Abs_Lumber=(A_EMG(:,2))+(A_EMG(:,4));
   R_Glutus_Peroneus=(A_EMG(:,5))+(A_EMG(:,13));
   L_Glutus_Peroneus=(A_EMG(:,6))+(A_EMG(:,14));
   R_R_Femoris_Ham=(A_EMG(:,7))+(A_EMG(:,9));
   L_R_Femoris_Ham=(A_EMG(:,8))+(A_EMG(:,10));
   R_Tibialis_Gastro=(A_EMG(:,11))+(A_EMG(:,15));
   L_Tibialis_Gastro=(A_EMG(:,12))+(A_EMG(:,16));
   R_Tibialis_Peroneus=(A_EMG(:,11))+(A_EMG(:,13));
   L_Tibialis_Peroneus=(A_EMG(:,12))+(A_EMG(:,14));


    for i=2:2:16
```

```
        EMG(:,i)=EMG(:,i).*(-1);

    end



    end
    save(['Ballet_Demi_2nd_',number])
    end
end

figure
subplot(9,2,1)
    P_Fx=plot(Fx,'g');hold on;%%saveas(P_Fx,',.fig') %% for R/L
direction(figure 1)should find out the platform movement from this graph
    subplot(9,2,2) %% for A/P direction
    P_Fy=plot(Fy,'g');hold on

    %%Abs and Lumber
    subplot(9,2,3)
    R_Abs=plot(A_EMG(:,1),'b');hold on;
    subplot(9,2,5)
    L_Abs=plot(A_EMG(:,2),'r');hold on;
    subplot(9,2,4)
    R_Lumber=plot(A_EMG(:,3),'b');hold on;
    subplot(9,2,6)
    L_Lumber=plot(A_EMG(:,4),'r');hold on;

    %%Glutus and Proneus
    subplot(9,2,7)
    R_Glutus=plot(A_EMG(:,5),'b');hold on;
    subplot(9,2,9)
    L_Glutus=plot(A_EMG(:,6),'r');hold on;
    subplot(9,2,8)
    R_Peroneus=plot(A_EMG(:,13),'b');hold on;
    subplot(9,2,10)
    L_Peroneus=plot(A_EMG(:,14),'r');hold on;

   %%R_Femoris and Hamsting
    subplot(9,2,11)
    R_R_Femoris=plot(A_EMG(:,7),'b');hold on;
    subplot(9,2,13)
    L_R_Femoris=plot(A_EMG(:,8),'r');hold on;
    subplot(9,2,12)
    R_Ham=plot(A_EMG(:,9),'b');hold on;
    subplot(9,2,14)
    L_Ham=plot(A_EMG(:,10),'r');hold on;


    %%Tibialis and Gastro
    subplot(9,2,15)
    R_Tibialis=plot(A_EMG(:,11),'b');hold on;
    subplot(9,2,17)
    L_Tibialis=plot(A_EMG(:,12),'r');hold on;

    subplot(9,2,16)
    R_Gastro=plot(A_EMG(:,15),'b');hold on;
    subplot(9,2,18)
    L_Gastro=plot(A_EMG(:,16),'r');hold on;
```

Appendix 3.3- The main Matlab code for 3D Inverse Dynamics created by Blenkinsop (Phd these,2015) and edited by E.Huh

```
clear
clc

tic


SW_L=30;
warning('off','MATLAB:nearlySingularMatrix')

log_errors=cell(100,1);
log_count=1;
apen_r_y=0.001;
delay_filter=3; %type of filter to use (0 = none; 1 = lowpass; 2 = highpass;
3 = both)
low_pass=2;     %cutoff frequency
high_pass=0.2;  %cutoff frequency

% 1 = standing - eyes open - static (A);
% 2 = standing - eyes closed - static (B);
% 3 = standing - eyes open - SR (C);
% 4 = standing - eyes closed - SR (D);
% 5 = handstand - eyes open - static (A);
% 6 = handstand - eyes closed - static (B);
% 7 = handstand - eyes open - SR (C);
% 8 = handstand - eyes closed - SR (D);


TYPES=[1,2];

markers_low=10;  %lowpass cutoff for markers (0 = none)
FP_low=10;       %lowpass cutoff for force plates (0 = none)
hz=200;
dt=1/hz;


% % fix for Rob
% ROB_FIX=ones(8,3);
% ROB_FIX(3,:)=[4015,1502,547];
% ROB_FIX(4,:)=[594,567,530];
% ROB_FIX(7,:)=[2502,451,1];
% ROB_FIX(8,:)=[1708,440,1];

interpolate=0;  % Interpolate marker data to 2000 Hz (0 = no; 1 = yes)
%NOTE: if interpolate=0 then the force data will be down sampled to 200 Hz


% dir='C:\Users\psgb\Personal Documents - Not Backed
Up\VICON\Glen\Handstand\Learning\Learning\';
% dir='C:\Users\psgb\Personal Documents - Not Backed
Up\VICON\Glen\Handstand\Learning\Elite\';
dir='C:\Users\pseh\Personal Documents - Not Backed Up\personal
research\RavinaHuh\One leg - dancers\'
% dir='C:\Users\pseh\Personal Documents - Not Backed Up\personal
research\RavinaHuh\One leg - dancers\Linnea\Session 1\'
```

```
%dir='C:\Users\psgb\Personal Documents - Not Backed
Up\VICON\Glen\Handstand\Learning\Test\';

% dir='D:\Office PC\VICON\Glen\Handstand\Learning\Elite\';
%dir='D:\Office PC\VICON\Glen\Handstand\Learning\TEST\';


%Subject=['Subject_',sub,'\'];
%Session='Session_01\';

%COM_T_headers=[{'SDx'},'Rangex','mean_SVx','max_SVx','SD_SVx','ApEn_x'];
COM_T_headers=['SDx','Rangex','mean_SVx','max_SVx','SD_SVx','ApEn_x'];


subject_id=1;
subject_fix=[1,1,1,2,1,1,1,1,1,1,1,1,1,1,1];

% subject_fix=[1,1,1,1,1,1];
% new_s=[{'Subject_02\Session_09-2\'};...
%        {'Subject_04\Session_06-2\'};...
%        {'Subject_06\Session_09-2\'};...
%        {'Subject_11\Session_09-2\'};...
%        {'Subject_14\Session_08-2\'};...
%        {'Subject_19\Session_08-2\'}];

SUB_NUM=[{'02'},{'04'},{'06'},{'11'},{'14'},{'19'}];

ALL_EMG_DELAY=nan(12,6,2,15);
ALL_SUB_STRATEGY1=nan(30,6,12,2,15);
ALL_SUB_STRATEGY2=nan(30,6,12,2,15);
ALL_SUB_MOV_COR=nan(6000,6,12,2,15);
TORQ_COM=nan(6000,8,12,2,15);
PERC_1=nan(12,8,2,15);
PERC_2=nan(12,8,2,15);
PERC_3=nan(12,8,2,15);
%[1:6,8,9,11,13,15]
for SUBJ=1
    if SUBJ < 10
        Subject=['Subject_0',num2str(SUBJ),'\'];
        sub=['0',num2str(SUBJ)];
    else
        Subject=['Subject_',num2str(SUBJ),'\'];
        sub=num2str(SUBJ);
    end

%     Subject=new_s{SUBJ};
%     sub=num2str(SUB_NUM{SUBJ});


    %Subject='Patient 1\';

    sessions=1;
    Trials_NEW=5;

    MAX_T=nan(Trials_NEW,3,sessions);
    MIN_T=nan(Trials_NEW,3,sessions);
    MEAN_T=nan(Trials_NEW,3,sessions);
    SES_M=nan(hz*30,3,Trials_NEW,sessions);
```

```
    SES_COM=nan(hz*30,2,3,Trials_NEW,sessions);

    SES_COM_TRAJ=nan(Trials_NEW,6,sessions);
    OUT=nan(Trials_NEW,58,sessions);
    NUM_TRIALS=nan(sessions,1);
    DELAY=nan(Trials_NEW,16,sessions);
    SLIDE_DELAY=nan(1000,5,10,sessions);
    T_E=nan(Trials_NEW,sessions);
    outputSTD=nan(2,214);
    outputMEAN=nan(2,214);
    outputALL=nan(12,215,2);
    ALL_MOV_COR=nan(6000,6,12,2);
for s=1
    Session='Translation\';
    outadd=0;
for TYP=1:2

    trial_type=TYPES(TYP);
%     trial_type=1;

%    Session=['Session_0',num2str(s),'\'];

    COP=nan(20,24);
%     SWAY=nan(20,14);

    MARKERS=nan(hz*30,88*3,20);
    FP_ORIGIN=nan(hz*30,3,12);
    %Mlabels=cell(20,257);
    %NEW_JC=nan(hz*30,2,10,5);
    platform_trial=nan(12,1);
    direction=cell(12,1);
    DIR=nan(12,1);
    FP1=nan(hz*30,9,12);
    FP2=nan(hz*30,9,12);
    FP=nan(hz*30,5,12);
    ALL_EMG=nan(hz*30,16,12);
    trials=0;
    pp=nan(20,1);
    delay=nan(12,6);
    for T=1:12
        start_frame=1;

        if trial_type==1
            if T<10,
                Trial=['Moving_0',num2str(T),'.csv'];
            else
                Trial=['Moving_',num2str(T),'.csv'];
            end
        elseif trial_type==2
            if T<10,
                Trial=['Moving_Out_0',num2str(T),'.csv'];
            else
                Trial=['Moving_Out_',num2str(T),'.csv'];
            end
        end

%         if T<10,
%             Trial=['ST_Moving_0',num2str(T),'.txt'];
%         else
%             Trial=['ST_Moving_',num2str(T),'.txt'];
```

```
%         end

        %create filename
        file=[dir,Subject,Session,Trial];
%         file=[dir,Subject,Trial];

        try
            if interpolate==1

                % Raw markers and joint centre locations
                [a,b,c]=importdata(file);
                Mdata=a.data;
                    % Mlabels=a.colheaders;
                    temp=a.textdata(10,1);
                    temp{1}(end+1)=',';
                    t1=find(temp{:}==',');
                    t2=diff(t1)>1;
                    Mlabels=cell(1);
                    Mlabels{1}='FRAME';
                    for n=1:length(t2)
                       if t2(n)==1
                           Mlabels{n+1}=temp{1}(t1(n)+1:t1(n+1)-1);
                       else
                           Mlabels{n+1}=Mlabels{n};
                       end
                       if n==length(t2)
                           Mlabels{n+2}=Mlabels{n+1};
                           Mlabels{n+3}=Mlabels{n+1};
                       end
                    end

EXTRA_L={'LWRIST','RWRIST','LELBOW','RELBOW','LSHOULDER','RSHOULDER','CENTE
R','LFINGER','RFINGER','Left_2MP','Left_5MP','Right_2MP','Right_5MP'};

                    %LWRIST

m1=find(cellfun('isempty',strfind(Mlabels,'Left_MW'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Left_LW'))==0);
                    Mdata(:,200:202)=(Mdata(:,m1)+Mdata(:,m2))/2;    %LWRIST
                    % TEMP_M(:,1:3)=(Mdata(:,m1)+Mdata(:,m2))/2;    %LWRIST
                    Mlabels{200}=EXTRA_L{1};
                    Mlabels{201}=EXTRA_L{1};
                    Mlabels{202}=EXTRA_L{1};

                    %RWRIST

m1=find(cellfun('isempty',strfind(Mlabels,'Right_MW'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Right_LW'))==0);
                    Mdata(:,203:205)=(Mdata(:,m1)+Mdata(:,m2))/2;    %RWRIST
                    Mlabels{203}=EXTRA_L{2};
                    Mlabels{204}=EXTRA_L{2};
                    Mlabels{205}=EXTRA_L{2};

                    %LELBOW

m1=find(cellfun('isempty',strfind(Mlabels,'Left_ME'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Left_LE'))==0);
```

```
                    Mdata(:,206:208)=(Mdata(:,m1)+Mdata(:,m2))/2;    %LELBOW
                    Mlabels{206}=EXTRA_L{3};
                    Mlabels{207}=EXTRA_L{3};
                    Mlabels{208}=EXTRA_L{3};

                    %RELBOW

m1=find(cellfun('isempty',strfind(Mlabels,'Right_ME'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Right_LE'))==0);
                    Mdata(:,209:211)=(Mdata(:,m1)+Mdata(:,m2))/2;    %RELBOW
                    Mlabels{209}=EXTRA_L{4};
                    Mlabels{210}=EXTRA_L{4};
                    Mlabels{211}=EXTRA_L{4};

                    %LSHOULDER

m1=find(cellfun('isempty',strfind(Mlabels,'Left_Anterior_Shoulder'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Left_Posterior_Shoulder'))==0);

Mdata(:,212:214)=(Mdata(:,m1)+Mdata(:,m2))/2;    %LSHOULDER
                    Mlabels{212}=EXTRA_L{5};
                    Mlabels{213}=EXTRA_L{5};
                    Mlabels{214}=EXTRA_L{5};

                    %RSHOULDER

m1=find(cellfun('isempty',strfind(Mlabels,'Right_Anterior_Shoulder'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Right_Posterior_Shoulder'))==0);

Mdata(:,215:217)=(Mdata(:,m1)+Mdata(:,m2))/2;    %RSHOULDER
                    Mlabels{215}=EXTRA_L{6};
                    Mlabels{216}=EXTRA_L{6};
                    Mlabels{217}=EXTRA_L{6};

                    %CENTER

mFL=find(cellfun('isempty',strfind(Mlabels,'Head_F_Left'))==0);
                    HFL=(Mdata(:,mFL));

mFR=find(cellfun('isempty',strfind(Mlabels,'Head_F_Right'))==0);
                    HFR=(Mdata(:,mFR));

mBL=find(cellfun('isempty',strfind(Mlabels,'Head_B_Left'))==0);
                    HBL=(Mdata(:,mBL));

mBR=find(cellfun('isempty',strfind(Mlabels,'Head_B_Right'))==0);
                    HBR=(Mdata(:,mBR));
                      %% Intersection :not working anyway
                    %  nA = dot(cross(HBR-HBL,HFL-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  nB = dot(cross(HFR-HFL,HFL-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  d = dot(cross(HFR-HFL,HBR-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  A0 = HFL + (nA/d)*(HFR-HFL);
                    %  B0 = HBL + (nB/d)*(HBR-HBL);
```

```
                    %% Simpler intersection
                    Head1=(HFL+HBR)/2;
                    Head2=(HFR+HBL)/2;
                    CENTER=(Head1+Head2)/2;

                    Mdata(:,218:220)=(Mdata(:,m1)+Mdata(:,m2))/2;    %
CENTER (HEAD)
                    Mlabels{218}=EXTRA_L{7};
                    Mlabels{219}=EXTRA_L{7};
                    Mlabels{220}=EXTRA_L{7};

%                     figure
%
%                     plot(Head1(1,1),Head1(1,2),'ro')
%                     hold on
%                     plot(Head2(1,1),Head2(1,2),'go')
%                     hold on
%                     plot(HFL(1,1),HFL(1,2),'yo')
%                     hold on
%                     plot(HFR(1,1),HFR(1,2),'yo')
%                     hold on
%                     plot(HBR(1,1),HBR(1,2),'yo')
%                     hold on
%                     plot(HBL(1,1),HBL(1,2),'yo')
%                     hold on
%                     plot(CENTER(1,1),CENTER(1,2))

                    %%%Hands

m1=find(cellfun('isempty',strfind(Mlabels,'Left_3MP'))==0);

m2=find(cellfun('isempty',strfind(Mlabels,'Right_3MP'))==0);
                    % LFINGER(:,1)=(Mdata(:,77)+(Mdata(:,77)-Mdata(:,200)));
                    % LFINGER(:,2)=(Mdata(:,78));
                    % LFINGER(:,3)=(Mdata(:,79)+(Mdata(:,79)-Mdata(:,202)));

                    LFINGER(:,1)=(Mdata(:,m1(:,1))+(Mdata(:,m1(:,1))-
Mdata(:,200)));
                    LFINGER(:,2)=(Mdata(:,m1(:,2))+(Mdata(:,m1(:,2))-
Mdata(:,201)));
                    LFINGER(:,3)=(Mdata(:,m1(:,3))+(Mdata(:,m1(:,3))-
Mdata(:,202)));
%                     figure;
%                     plot(LFINGER(:,1),LFINGER(:,3),'ro');
%                     hold on
%                     plot(Mdata(:,m1(:,1)),Mdata(:,m1(:,3)),'yo');
%                     hold on
%                     plot(Mdata(:,200),Mdata(:,202),'bo');

                    Mdata(:,221:223)=(LFINGER(:,1:3));    % LFINGER
                    Mlabels{221}=EXTRA_L{8};
                    Mlabels{222}=EXTRA_L{8};
                    Mlabels{223}=EXTRA_L{8};

                    RFINGER(:,1)=(Mdata(:,m2(:,1))+(Mdata(:,m2(:,1))-
Mdata(:,203)));
                    RFINGER(:,2)=(Mdata(:,m2(:,2))+(Mdata(:,m2(:,2))-
Mdata(:,204)));
                    RFINGER(:,3)=(Mdata(:,m2(:,3))+(Mdata(:,m2(:,3))-
Mdata(:,205)));
```

```
%                       figure;
%                       plot(RFINGER(:,1),RFINGER(:,3),'ro');
%                       hold on
%                       plot(Mdata(:,m2(:,1)),Mdata(:,m2(:,3)),'yo');
%                       hold on
%                       plot(Mdata(:,203),Mdata(:,205),'bo');

                    Mdata(:,224:226)=(RFINGER(:,1:3));    % RFINGER
                    Mlabels{224}=EXTRA_L{9};
                    Mlabels{225}=EXTRA_L{9};
                    Mlabels{226}=EXTRA_L{9};

                    %% Left_2MP and Left_5MP

m1=find(cellfun('isempty',strfind(Mlabels,'Left_3MP'))==0);
                    Left_2MP=(Mdata(:,m1));
                    Left_5MP=(Mdata(:,m1));
                    Mdata(:,227:229)=(Left_2MP(:,1:3));
                    Mdata(:,230:232)=(Left_5MP(:,1:3));
                    Mlabels{227}=EXTRA_L{10}; %%Left_2MP
                    Mlabels{228}=EXTRA_L{10};
                    Mlabels{229}=EXTRA_L{10};
                    Mlabels{230}=EXTRA_L{11}; %%Left_5MP
                    Mlabels{231}=EXTRA_L{11};
                    Mlabels{232}=EXTRA_L{11};

                    %% Right_2MP and Right_5MP

m2=find(cellfun('isempty',strfind(Mlabels,'Right_3MP'))==0);
                    Right_2MP=(Mdata(:,m2));
                    Right_5MP=(Mdata(:,m2));
                    Mdata(:,233:235)=(Right_2MP(:,1:3));
                    Mdata(:,236:238)=(Right_5MP(:,1:3));
                    Mlabels{233}=EXTRA_L{12}; %%Right_2MP
                    Mlabels{234}=EXTRA_L{12};
                    Mlabels{235}=EXTRA_L{12};
                    Mlabels{236}=EXTRA_L{13}; %%Right_5MP
                    Mlabels{237}=EXTRA_L{13};
                    Mlabels{238}=EXTRA_L{13};


                    [a,b,c]=importdata(file,',',size(a.data,1)+c+5);
                    Adata=a.data;
                    Alabels=a.colheaders;

                    [a,b,c]=importdata(file,',',size(a.data,1)+c+11);
                    Fdata=a.data;
                    Flabels=a.colheaders;

                    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
                Mdata=nan(size(a.data,1)*10,size(a.data,2));
                Mlabels(T,1:length(a.colheaders))=a.colheaders;

                % Interpolate marker data from 200Hz to 2000Hz
                for sp=2:size(a.data,2);

Mdata(:,sp)=spline(a.data(:,1),a.data(:,sp),[1:0.1:size(a.data,1)+0.9]');
                end
```

```
                % Collect event information for end of trial
                if size(a.textdata,1)>2,
                    event=a.textdata{3,1};
                    dp=strfind(event,'.');  %find decimal point in event
string
                    for v=1:3
                        if str2double(event(dp-v:dp+4))>0,
                            trial_end=str2double(event(dp-v:dp+4))+10/hz;
                        end
                    end
                else
                    trial_end=size(Mdata,1)/hz;
                end

            else
                % Raw markers and joint centre locations
                [a,b,c]=importdata(file);
                Mdata=a.data;
                Mlabels(T,1:length(a.colheaders))=a.colheaders;

                % Collect event information for end of trial
                if size(a.textdata,1)>2,
                    event=a.textdata{3,1};
                    dp=strfind(event,'.');  %find decimal point in event
string
                    for v=1:3
                        if str2double(event(dp-v:dp+4))>0,
                            trial_end=str2double(event(dp-v:dp+4))+1/hz;
                        end
                    end
                else
                    trial_end=size(Mdata,1)/hz;
                end

            end


            last_frame=floor(trial_end*hz);
            pp(T,1)=trial_end;

        % Analog (EMG)
        [a,b,c]=importdata(file,'\t',size(a.data,1)+c+5);
        Adata=a.data;
        Alabels=a.colheaders;

        % Force Plates
        [a,b,c]=importdata(file,'\t',size(a.data,1)+c+11);
        Fdata=a.data(:,2:end);
        Flabels=a.colheaders;
        %replace nans with zeros
        Fdata(isnan(Fdata))=0;


        clear a b c

        fp1=copf2(Fdata,1000); %seperate force plates
        fp0=copf(Fdata,1000);  %combined force plates
        if interpolate==1
            fp2=fp1;
```

```
        fp=fp0;
        clear fp1
    else
        if subject_fix(SUBJ)==1
            % normal trial - sample rate 2000 Hz
            dec=10;
            fp2=nan(size(fp1,1)/dec,size(fp1,2));
            for w=1:size(fp2,2)
                fp2(:,w)=decimate(fp1(:,w),dec,'fir');
            end

            fp=nan(size(fp0,1)/dec,size(fp0,2));
            for w=1:size(fp0,2)
                fp(:,w)=decimate(fp0(:,w),dec,'fir');
            end

            %get EMG, remove 48 ms delay, and pad end with zeros
            RAW_EMG=[Adata(97:end,14:29);zeros(96,16)]; % 96 samples

            %bandpass filter
            RAW_EMG=abs(Filtmat(1/2000,[20 500],4,RAW_EMG,'bandpass'));

            %down sample
            EMG=nan(size(RAW_EMG,1)/dec,size(RAW_EMG,2));
            for w=1:16
                EMG(:,w)=decimate(RAW_EMG(:,w),dec,'fir');
            end

            trigger=decimate(Adata(:,31),dec,'fir');

            if isempty(find(trigger > 0,1,'first'))
                start_time=1;
            else
                start_time=find(trigger > 0,1,'first');
            end

            clear fp1 fp0
        elseif subject_fix(SUBJ)==2
            %messed up sample rate (1800 Hz)
            dec=9;
            fp2=nan(size(fp1,1)/dec,size(fp1,2));
            for w=1:size(fp2,2)
                fp2(:,w)=decimate(fp1(:,w),dec,'fir');
            end

            fp=nan(size(fp0,1)/dec,size(fp0,2));
            for w=1:size(fp0,2)
                fp(:,w)=decimate(fp0(:,w),dec,'fir');
            end


            %get EMG, remove 48 ms delay, and pad end with zeros
            RAW_EMG=[Adata(88:end,14:29);zeros(87,16)]; % 87 samples

            %bandpass filter
            RAW_EMG=abs(Filtmat(1/1800,[20 500],4,RAW_EMG,'bandpass'));

            %down sample
            EMG=nan(size(RAW_EMG,1)/dec,size(RAW_EMG,2));
```

```
        for w=1:16
            EMG(:,w)=decimate(RAW_EMG(:,w),dec,'fir');
        end

        trigger=decimate(Adata(:,31),dec,'fir');

        if isempty(find(trigger > 0,1,'first'))
            start_time=1;
        else
            start_time=find(trigger > 0,1,'first');
        end

        clear fp1 fp0

    elseif subject_fix(SUBJ)==3
        %messed up sample rate (1000 Hz)
        dec=5;
        fp2=nan(size(fp1,1)/dec,size(fp1,2));
        for w=1:size(fp2,2)
            fp2(:,w)=decimate(fp1(:,w),dec,'fir');
        end

        fp=nan(size(fp0,1)/dec,size(fp0,2));
        for w=1:size(fp0,2)
            fp(:,w)=decimate(fp0(:,w),dec,'fir');
        end


        %get EMG, remove 48 ms delay, and pad end with zeros
        RAW_EMG=[Adata(88:end,14:29);zeros(87,16)]; % 87 samples

        %bandpass filter
        RAW_EMG=abs(Filtmat(1/1000,[20 400],4,RAW_EMG,'bandpass'));

        %down sample
        EMG=nan(size(RAW_EMG,1)/dec,size(RAW_EMG,2));
        for w=1:16
            EMG(:,w)=decimate(RAW_EMG(:,w),dec,'fir');
        end

        trigger=decimate(Adata(:,31),dec,'fir');

        if isempty(find(trigger > 0,1,'first'))
            start_time=1;
        else
            start_time=find(trigger > 0,1,'first');
        end

        clear fp1 fp0
    end
end


% Apply Filters
if FP_low==0
    fp1=fp2(1:last_frame,:);
    fp0=fp(1:last_frame,:);
else
```

```
            fp1=Filtmat(dt,FP_low,4,fp2);
            fp1=fp1(1:last_frame,:);
            fp0=Filtmat(dt,FP_low,4,fp);
            fp0=fp0(1:last_frame,:);
        end


        if markers_low==0
            Mdata=Mdata(1:last_frame,:);
        else
            Mdata=Filtmat(dt,markers_low,4,Mdata);
            Mdata=Mdata(1:last_frame,:);
        end

%         if SUBJ==2
%             start_time=ROB_FIX(trial_type,T);
%         end
%         %offset for start time and end time
%         if start_time > 1
%             disp('here')
%             fp1=fp1(start_time:last_frame,:);
%             fp0=fp0(start_time:last_frame,:);
%
%             Mdata=Mdata(start_time:last_frame,:);
%             EMG=EMG(start_time:last_frame,:);
%
%             pp(T,1)=(last_frame-start_time+1)/hz;
%         end

        %EMG
        ALL_EMG(1:size(EMG,1),:,T)=EMG;

%==========================================================================
% Need to do force plate correction
%==========================================================================

        corners=[{'FP1_FL'},{'FP2_FR'},{'FP2_FL'},{'FP2_BL'}];
        FP_O=nan(size(Mdata,1),3,length(corners));
        for ori=1:length(corners)

mod=find(cellfun('isempty',strfind(Mlabels(T,:),corners{ori}))==0);

FP_O(:,:,ori)=Filtmat(1/hz,10,4,[Mdata(:,mod(1)),Mdata(:,mod(2)),Mdata(:,mo
d(3))])/1000;
        end



         %Create rotation matrix and quaternion for platform motion
         P1=FP_O(:,:,1)-FP_O(:,:,2); %x axis
         P2=FP_O(:,:,4)-FP_O(:,:,3); %y axis
         P1=P1./(sqrt(sum(P1.^2,2))*[1 1 1]);
         P2=P2./(sqrt(sum(P2.^2,2))*[1 1 1]);
         P3=cross(P1,P2,2); %z axis
         P3=P3./(sqrt(sum(P3.^2,2))*[1 1 1]);
         P2=cross(P3,P1,2); %re-calculate y axis
         PR1=[permute(P1,[3,2,1]);permute(P2,[3,2,1]);permute(P3,[3,2,1])];

         FP_C=mean(FP_O(:,:,3:4),3);
```

```
FP_ACC=glen_diff(glen_diff(Filtmat(1/hz,10,4,FP_C),hz),hz);

FP_mass=29;

%save force plate motion for COM correction in delays
FP_ORIGIN(1:size(Mdata,1),:,T)=FP_O(:,:,3);


%COP correction [QLD(R,COP,ORIGIN)]
COP1_COR=QLD(PR1,[fp1(:,1:2),zeros(size(fp1,1),1)],FP_O(:,:,3));
COP2_COR=QLD(PR1,[fp1(:,9:10),zeros(size(fp1,1),1)],FP_O(:,:,3));

%apply correction
fp1(:,1:2)=COP1_COR(:,2:3);
fp1(:,9:10)=COP2_COR(:,2:3);

%force correction [QLD(R,[0,0,0],ORIGIN)]
F1_COR=QLD(PR1,[0 0 0],fp1(:,3:5)-FP_ACC*FP_mass);
F2_COR=QLD(PR1,[0 0 0],fp1(:,11:13)-FP_ACC*FP_mass);

fp1(:,3:5)=F1_COR(:,2:4);
fp1(:,11:13)=F2_COR(:,2:4);


%Calculate free moments from each foce plate
t=zeros(size(fp1,1),3,2);
t(:,3,1)=(fp1(:,8)+(fp1(:,3).*fp1(:,2))-(fp1(:,4).*fp1(:,1)));
t(:,3,2)=(fp1(:,16)+(fp1(:,11).*fp1(:,10))-(fp1(:,12).*fp1(:,9)));

%Save COP, FORCE, and MOMENT data
FP1(1:size(fp1,1),:,T)=[COP1_COR(:,2:4),-fp1(:,3:5),t(:,:,1)];
FP2(1:size(fp1,1),:,T)=[COP1_COR(:,2:4),-fp1(:,11:13),t(:,:,2)];

%combined force plate


fp0=[fp1(:,1:2),zeros(size(fp1,1),4),fp1(:,3:8),fp1(:,9:10),zeros(size(fp1,
1),4),fp1(:,11:16)];
FP(1:size(fp1,1),:,T)=copf(fp0);

%Save Markers
MARKERS(1:size(Mdata,1),1:size(Mdata,2),T)=Mdata;




%==========================================================================
%==========================================================================


%Find start time of platform translation (nearest 5ms)

FP_diff=mean(FP_C(1:hz,:));
```

```
        if isempty(find((FP_C(:,2)-
FP_diff(2))>std(FP_C(1:hz,2))*20,1,'first'))
            platform=find((FP_C(:,2)-FP_diff(2))<std(FP_C(1:hz,2))*-
20,1,'first');
        else
            platform=find((FP_C(:,2)-
FP_diff(2))>std(FP_C(1:200,2))*20,1,'first');
        end

        platform_trial(T,1)=platform;


        if max(FP_O(:,2)-FP_O(1,2))>0.025
            if max(abs(glen_diff(FP_C(:,2),hz))) > 0.15
                direction(T,1)={'Backward Fast'};
                DIR(T,1)=1;
            else
                direction(T,1)={'Backward Slow'};
                DIR(T,1)=2;
            end

            for std_t=3:5

                %only look and EMG 3 & 4
                temp1=EMG(:,3)+EMG(:,4);
                f1=find(temp1(platform:end) >
mean(temp1(1:platform))+std(temp1(1:platform))*std_t,1,'first')*5;
                if isempty(f1)
                    f1=nan;
                end


                %only look and EMG 1 & 2
                temp2=EMG(:,1)+EMG(:,2);
                f2=find(temp2(platform:end) >
mean(temp2(1:platform))+std(temp2(1:platform))*std_t,1,'first')*5;
                if isempty(f2)
                    f2=nan;
                end

                delay(T,std_t*2-5:std_t*2-4)=[f1,f2];
            end


        elseif min(FP_O(:,2)-FP_O(1,2))<-0.025
            if max(abs(glen_diff(FP_C(:,2),hz))) > 0.15
                direction(T,1)={'Forward Fast'};
                DIR(T,1)=3;
            else
                direction(T,1)={'Forward Slow'};
                DIR(T,1)=4;
            end

            for std_t=3:5
                %only look and EMG 1 & 2
                temp1=EMG(:,1)+EMG(:,2);
                f1=find(temp1(platform:end) >
mean(temp1(1:platform))+std(temp1(1:platform))*std_t,1,'first')*5;
                if isempty(f1)
```

```
                    f1=nan;
                end


                %only look and EMG 3 & 4
                temp2=EMG(:,3)+EMG(:,4);
                f2=find(temp2(platform:end) >
mean(temp2(1:platform))+std(temp2(1:platform))*std_t,1,'first')*5;
                if isempty(f2)
                    f2=nan;
                end

                delay(T,std_t*2-5:std_t*2-4)=[f1,f2];
            end

        end



%==========================================================================
%==========================================================================



        trials=trials+1;

        catch exception1
            warning([exception1.message,' -
',num2str(SUBJ),'/',num2str(s),'/',num2str(T)])
            log_errors{log_count}=[exception1.message,' - Line:
',num2str(exception1.stack(end).line),' -
',num2str(SUBJ),'/',num2str(s),'/',num2str(T)];
            log_count=log_count+1;
        end

    end

    ALL_EMG_DELAY(:,:,TYP,SUBJ)=delay;

    T_E(1:size(pp,1),s)=pp;

    %Calculate the subject mass for this session
    subject_mass='subject_mass.mat'
%     subject_mass=[dir,Subject,Session,'subject_mass'];

%==========================================================================
% Segment Inertia Data
%==========================================================================
      if trial_type==1
        %open static trial
        file=[dir,Subject,Session,'Static_01.csv'];
%         file=[dir,Subject,'Static_01.txt'];
        %file='C:\Users\pseh\Personal Documents - Not Backed Up\personal
research\RavinaHuh\One leg - dancers\Linnea\Session 1\Static_01.csv'

        ai=importdata(file,',');
        temp_Mdata=ai.data;
%         temp_Mlabels=ai.colheaders;
```

```
        temp=ai.textdata(10,1);
        temp{1}(end+1)=',';
        t1=find(temp{:}==',');
        t2=diff(t1)>1;
        temp_Mlabels=cell(1);
        temp_Mlabels{1}='FRAME';
        for n=1:length(t2)
           if t2(n)==1
               temp_Mlabels{n+1}=temp{1}(t1(n)+1:t1(n+1)-1);
           else
               temp_Mlabels{n+1}=temp_Mlabels{n};
           end
           if n==length(t2)
               temp_Mlabels{n+2}=temp_Mlabels{n+1};
               temp_Mlabels{n+3}=temp_Mlabels{n+1};
           end
        end

EXTRA_L={'LWRIST','RWRIST','LELBOW','RELBOW','LSHOULDER','RSHOULDER','CENTE
R','LFINGER','RFINGER','Left_2MP','Left_5MP','Right_2MP','Right_5MP'};

                    %LWRIST

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_MW'))==0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Left_LW'))==0);

temp_Mdata(:,200:202)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;   %LWRIST
                    % TEMP_M(:,1:3)=(Mdata(:,m1)+Mdata(:,m2))/2;   %LWRIST
                    temp_Mlabels{200}=EXTRA_L{1};
                    temp_Mlabels{201}=EXTRA_L{1};
                    temp_Mlabels{202}=EXTRA_L{1};

                    %RWRIST

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Right_MW'))==0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_LW'))==0);

temp_Mdata(:,203:205)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;   %RWRIST
                    temp_Mlabels{203}=EXTRA_L{2};
                    temp_Mlabels{204}=EXTRA_L{2};
                    temp_Mlabels{205}=EXTRA_L{2};

                    %LELBOW

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_ME'))==0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Left_LE'))==0);

temp_Mdata(:,206:208)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;   %LELBOW
                    temp_Mlabels{206}=EXTRA_L{3};
                    temp_Mlabels{207}=EXTRA_L{3};
                    temp_Mlabels{208}=EXTRA_L{3};

                    %RELBOW

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Right_ME'))==0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_LE'))==0);
```

```
temp_Mdata(:,209:211)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;    %RELBOW
                    temp_Mlabels{209}=EXTRA_L{4};
                    temp_Mlabels{210}=EXTRA_L{4};
                    temp_Mlabels{211}=EXTRA_L{4};

                    %LSHOULDER

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_Anterior_Shoulder'))==
0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Left_Posterior_Shoulder'))=
=0);

temp_Mdata(:,212:214)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;    %LSHOULDER
                    temp_Mlabels{212}=EXTRA_L{5};
                    temp_Mlabels{213}=EXTRA_L{5};
                    temp_Mlabels{214}=EXTRA_L{5};

                    %RSHOULDER

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Right_Anterior_Shoulder'))=
=0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_Posterior_Shoulder'))
==0);

temp_Mdata(:,215:217)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;    %RSHOULDER
                    temp_Mlabels{215}=EXTRA_L{6};
                    temp_Mlabels{216}=EXTRA_L{6};
                    temp_Mlabels{217}=EXTRA_L{6};

                    %CENTER

mFL=find(cellfun('isempty',strfind(temp_Mlabels,'Head_F_Left'))==0);
                    HFL=(temp_Mdata(:,mFL));

mFR=find(cellfun('isempty',strfind(temp_Mlabels,'Head_F_Right'))==0);
                    HFR=(temp_Mdata(:,mFR));

mBL=find(cellfun('isempty',strfind(temp_Mlabels,'Head_B_Left'))==0);
                    HBL=(temp_Mdata(:,mBL));

mBR=find(cellfun('isempty',strfind(temp_Mlabels,'Head_B_Right'))==0);
                    HBR=(temp_Mdata(:,mBR));
                      %% Intersection :not working anyway
                    %  nA = dot(cross(HBR-HBL,HFL-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  nB = dot(cross(HFR-HFL,HFL-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  d = dot(cross(HFR-HFL,HBR-HBL),cross(HFR-HFL,HBR-
HBL));
                    %  A0 = HFL + (nA/d)*(HFR-HFL);
                    %  B0 = HBL + (nB/d)*(HBR-HBL);

                    %% Simpler intersection
                    Head1=(HFL+HBR)/2;
                    Head2=(HFR+HBL)/2;
                    CENTER=(Head1+Head2)/2;
```

```
temp_Mdata(:,218:220)=(temp_Mdata(:,m1)+temp_Mdata(:,m2))/2;    % CENTER
(HEAD)
                    temp_Mlabels{218}=EXTRA_L{7};
                    temp_Mlabels{219}=EXTRA_L{7};
                    temp_Mlabels{220}=EXTRA_L{7};


                    %%%Hands

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_3MP'))==0);

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_3MP'))==0);
                    % LFINGER(:,1)=(Mdata(:,77)+(Mdata(:,77)-Mdata(:,200)));
                    % LFINGER(:,2)=(Mdata(:,78));
                    % LFINGER(:,3)=(Mdata(:,79)+(Mdata(:,79)-Mdata(:,202)));


LFINGER(:,1)=(temp_Mdata(:,m1(:,1))+(temp_Mdata(:,m1(:,1))-
temp_Mdata(:,200)));

LFINGER(:,2)=(temp_Mdata(:,m1(:,2))+(temp_Mdata(:,m1(:,2))-
temp_Mdata(:,201)));

LFINGER(:,3)=(temp_Mdata(:,m1(:,3))+(temp_Mdata(:,m1(:,3))-
temp_Mdata(:,202)));

                    temp_Mdata(:,221:223)=(LFINGER(:,1:3));    % LFINGER
                    temp_Mlabels{221}=EXTRA_L{8};
                    temp_Mlabels{222}=EXTRA_L{8};
                    temp_Mlabels{223}=EXTRA_L{8};


RFINGER(:,1)=(temp_Mdata(:,m2(:,1))+(temp_Mdata(:,m2(:,1))-
temp_Mdata(:,203)));

RFINGER(:,2)=(temp_Mdata(:,m2(:,2))+(temp_Mdata(:,m2(:,2))-
temp_Mdata(:,204)));

RFINGER(:,3)=(temp_Mdata(:,m2(:,3))+(temp_Mdata(:,m2(:,3))-
temp_Mdata(:,205)));


                    temp_Mdata(:,224:226)=(RFINGER(:,1:3));    % RFINGER
                    temp_Mlabels{224}=EXTRA_L{9};
                    temp_Mlabels{225}=EXTRA_L{9};
                    temp_Mlabels{226}=EXTRA_L{9};

                    %% Left_2MP and Left_5MP

m1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_3MP'))==0);
                    Left_2MP=(temp_Mdata(:,m1));
                    Left_5MP=(temp_Mdata(:,m1));
                    temp_Mdata(:,227:229)=(Left_2MP(:,1:3));
                    temp_Mdata(:,230:232)=(Left_5MP(:,1:3));
                    temp_Mlabels{227}=EXTRA_L{10}; %%Left_2MP
                    temp_Mlabels{228}=EXTRA_L{10};
                    temp_Mlabels{229}=EXTRA_L{10};
                    temp_Mlabels{230}=EXTRA_L{11}; %%Left_5MP
                    temp_Mlabels{231}=EXTRA_L{11};
```

```
                    temp_Mlabels{232}=EXTRA_L{11};

                    %% Right_2MP and Right_5MP

m2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_3MP'))==0);
                    Right_2MP=(temp_Mdata(:,m2));
                    Right_5MP=(temp_Mdata(:,m2));
                    temp_Mdata(:,233:235)=(Right_2MP(:,1:3));
                    temp_Mdata(:,236:238)=(Right_5MP(:,1:3));
                    temp_Mlabels{233}=EXTRA_L{12}; %%Right_2MP
                    temp_Mlabels{234}=EXTRA_L{12};
                    temp_Mlabels{235}=EXTRA_L{12};
                    temp_Mlabels{236}=EXTRA_L{13}; %%Right_5MP
                    temp_Mlabels{237}=EXTRA_L{13};
                    temp_Mlabels{238}=EXTRA_L{13};
        %Calculate markers distances for extra bits for torso
        hip1=find(cellfun('isempty',strfind(temp_Mlabels,'RHJC'))==0);
        hip2=find(cellfun('isempty',strfind(temp_Mlabels,'LHJC'))==0);
        hip=mean((temp_Mdata(:,hip1(3))+temp_Mdata(:,hip2(3)))/2);
        psis1=find(cellfun('isempty',strfind(temp_Mlabels,'Left_PSIS'))==0);

psis2=find(cellfun('isempty',strfind(temp_Mlabels,'Right_PSIS'))==0);
        PSIS=mean((temp_Mdata(:,psis1(3))+temp_Mdata(:,psis2(3)))/2);

T10=mean(temp_Mdata(:,find(cellfun('isempty',strfind(temp_Mlabels,'T10:Z'))
==0)));
        sh1=find(cellfun('isempty',strfind(temp_Mlabels,'RSHOULDER'))==0);
        sh2=find(cellfun('isempty',strfind(temp_Mlabels,'LSHOULDER'))==0);
        SHOULDER=mean((temp_Mdata(:,sh1(3))+temp_Mdata(:,sh2(3)))/2);

C7=mean(temp_Mdata(:,find(cellfun('isempty',strfind(temp_Mlabels,'C7:Z'))==
0)));

        %Record extra bits in testS file
        dis=[hip-hip;PSIS-hip;T10-hip;SHOULDER-hip;C7-hip];


        %get inertia data
%         [inertia1,inertia2]=inert(['1' sub],subject_mass,dis);
% %         [inertia1,inertia2]=inert(['1' sub],subject_mass,dis,1); %from
home
% %         [inertia1,inertia2]=inert(sub,subject_mass,dis);
%       else
%           [inertia1,inertia2]=inertA('testI','testG');
%       end
%
%         inertia=[inertia1;inertia2(:,1:6)]; %use extra bits for torso
%
% %         I=INERTIA([{'Right Hand'};{'Right Forearm'};{'Right Upper
arm'}],3,inertia,1);
%         ILa=INERTIA([{'Left Hand'},{'Left Forearm'},{'Left Upper
Arm'},{'Left SG'}],3,inertia);
%         ILl=INERTIA([{'Left Foot'},{'Left Shank'},{'Left
Thigh'}],3,inertia);
%         IRa=INERTIA([{'Right Hand'},{'Right Forearm'},{'Right Upper
Arm'},{'Right SG'}],3,inertia);
%         IRl=INERTIA([{'Right Foot'},{'Right Shank'},{'Right
Thigh'}],3,inertia);
%
IC=INERTIA([{'Pelvis'},{'Abdomen'},{'Thorax'},{'Head'}],3,inertia);
```

```
%
%         %Store all inertia data in one matrix
%         SEGI=ILa;
%         SEGI(5:7,:)=ILl;
%         SEGI(8:11,:)=IRa;
%         SEGI(12:14,:)=IRl;
%         SEGI(15:18,:)=IC;


       SEGI_labels=[{'Mass'},{'Distance'},{'Length'},{'Inertia
X'},{'Inertia Y'},{'Inertia Z'}]
       SEGI_Segments=[{'Head'};{'Trunk'};{'Left Upperarm'};{'Right
Upperarm'};{'Left Forearm'};{'Right Forearm'};{'Left Hand'};{'Right
Hand'};{'Left Thigh'};{'Right Thigh'};{'Left Calf'};{'Right Calf'};{'Left
Foot'};{'Right Foot'}];
       %%SEGI should input manually


% Example of how the kinetic chain will connect
%==========================================================================
% Segments/Joints
%==========================================================================
%   Right                   Left                    Joints
%--------------------------------------------------------------------------
%   Hand                    Hand
%     |                       |                     WRISTS
%   Forearm                 Forearm
%     |                       |                     ELBOWS
%    Arm                     Arm
%     |        [terminal]     |                     SHOULDERS
%  Shoulder      Head &    Shoulder
%   Girdle       Neck       Girdle
%           \      |      /                         CLAVICAL/NECK
%                Thorax
%                  |                                THORACIC SPINE
%                Abdomin
%                  |                                LUMBAR SPINE
%                Pelvis
%              /        \
%             /          \                          HIPS
%          Thigh         Thigh
%            |             |                       KNEES
%          Shank         Shank
%            |             |                       ANKLES
%           Foot          Foot
%==========================================================================


        % 3D inverse dynamics
        COM=nan(size(MARKERS,1),3,3,trials);
        ALLQ=nan(size(MARKERS,1),4,5,size(SEGI,1),trials);
        WR=nan(size(MARKERS,1),6,size(SEGI,1),trials);
        ALL_adjust=nan(trials,6);
        for m=1:trials
            try

                last_frame=floor(pp(m)*hz);
%==========================================================================
% KINEMATICS
%==========================================================================
```

```
                % Gather segment data

[SMLa,axesLa]=segment_markers(MARKERS(1:last_frame,:,m),Mlabels(m,:),[{'LHA
ND'},{'LFOREARM'},{'LARM'},{'LSG'}]);

[SMLl,axesLl]=segment_markers(MARKERS(1:last_frame,:,m),Mlabels(m,:),[{'LFO
OT'},{'LSHANK'},{'LTHIGH'}]);

[SMRa,axesRa]=segment_markers(MARKERS(1:last_frame,:,m),Mlabels(m,:),[{'RHA
ND'},{'RFOREARM'},{'RARM'},{'RSG'}]);

[SMRl,axesRl]=segment_markers(MARKERS(1:last_frame,:,m),Mlabels(m,:),[{'RFO
OT'},{'RSHANK'},{'RTHIGH'}]);

[SMC,axesC]=segment_markers(MARKERS(1:last_frame,:,m),Mlabels(m,:),[{'PELVI
S'},{'ABDOMEN'},{'THORAX'},{'HEAD'}]);

                %collate and track positions of segments
                limbs=[4,3,4,3,6];      %[Larm, Lleg, Rarm, Rleg, centre]
                SM=SMLa/1000;           %convert to metres
                SM(:,:,:,5:7)=SMLl/1000;
                SM(:,:,:,8:11)=SMRa/1000;
                SM(:,:,:,12:14)=SMRl/1000;
                SM(:,:,:,15:18)=SMC/1000;

                %redefine first defining line for ABDOMEN and THORAX
                SM(:,:,2,16)=(SMC(:,:,2,2)+SMC(:,:,2,1))/2000;
                SM(:,:,3,16)=(SMC(:,:,3,2)+SMC(:,:,3,1))/2000;
                SM(:,:,2,17)=(SMC(:,:,2,3)+SMC(:,:,2,2))/2000;
                SM(:,:,3,17)=(SMC(:,:,3,3)+SMC(:,:,3,2))/2000;

                axes=axesLa;
                axes(5:7)=axesLl;
                axes(8:11)=axesRa;
                axes(12:14)=axesRl;
                axes(15:18)=axesC;

                %calculate Segments COM positions in LCS (1:14 = limbs)
                %[ these should be relative to proximal joints, so will ]
                %[ be negitive when expressed in the LCS                ]
                SEG_COM=zeros(size(SM,1),3,size(SEGI,1));
                for p=1:14
                    SEG_COM(:,3,p)=-sqrt(sum((SM(:,:,1,p)-
SM(:,:,6,p)).^2,2))*(SEGI(p,2)./SEGI(p,3));
                end

                %COM for pelvis (hips to sacrum height)
                %this is relative to Sacrum so need y and z directions
                temp_com1=(SM(:,:,1,7)+SM(:,:,1,14))/2; %hip centres
                temp_com2=(SM(:,:,1,15)+SM(:,:,6,15))/2; %pelvis centre
                SEG_COM(:,2:3,15)=[sqrt(sum((SM(:,:,1,15)-
SM(:,:,6,15)).^2,2))*0.5,...
                    -sqrt(sum((temp_com1-
temp_com2).^2,2))*(SEGI(15,2)./SEGI(15,3))];

                %COM for abdomen (sacrum to T10)
                %this is relative to T10 so need y and z directions
                SEG_COM(:,2:3,16)=[sqrt(sum((SM(:,:,1,16)-
SM(:,:,6,16)).^2,2))*0.5,...
```

```
                    -sqrt(sum((SM(:,:,1,16)-
SM(:,:,1,17)).^2,2))*(SEGI(16,2)./SEGI(16,3))];

                %COM for thorax (T10 to C7)
                %this is relative to C7 so need y and z directions
                SEG_COM(:,2:3,17)=[sqrt(sum((SM(:,:,1,17)-
SM(:,:,6,17)).^2,2))*0.5,...
                    -sqrt(sum((SM(:,:,1,17)-
SM(:,:,2,17)).^2,2))*(SEGI(17,2)./SEGI(17,3))];

                %COM for head (use anthrops to get distance below headband)
                %this is relative to head centre so need just z direction
                SEG_COM(:,3,18)=SEGI(18,2)-sqrt(sum((SM(:,:,1,18)-
SM(:,:,6,18)).^2,2));

                %Calculate the 7D vector for joint centre and quaternion
                PQ=nan(size(SM,1),7,size(SM,4));
                limb=[{'SMLa'},{'SMLb'},{'SMRa'},{'SMRb'},{'SMC'}];

limb_axes=[{'axesLa'},{'axesLb'},{'axesRa'},{'axesRb'},{'axesC'}];

                COM0=zeros(size(SM,1),3);
                ALL_R=nan(3,3,size(SM,1),size(SEGI,1));
                for m2=1:size(SEG_COM,3) %SEGMENTS
                    %sort out rotation order
                    current_axis=axes{m2};

                    %Create rotation matrix
                    A1=(SM(:,:,2,m2)-SM(:,:,3,m2));
                    A2=(SM(:,:,4,m2)-SM(:,:,5,m2));
                    A1=A1./(sqrt(sum(A1.^2,2))*[1 1 1]);
                    A2=A2./(sqrt(sum(A2.^2,2))*[1 1 1]);

                    R=nan(size(SM,1),3,3);
                    R(:,:,str2double(current_axis(1)))=A1;
                    R(:,:,str2double(current_axis(3)))=A2;
                    if current_axis(2)=='1'
                        A3=cross(R(:,:,2),R(:,:,3),2); % x=yXz
                        R(:,:,1)=A3./(sqrt(sum(A3.^2,2))*[1 1 1]);
                        if current_axis(3)=='2'
                            A4=cross(R(:,:,3),R(:,:,1),2); % y=zXx
                            R(:,:,2)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                        else
                            A4=cross(R(:,:,1),R(:,:,2),2); % z=xXy
                            R(:,:,3)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                        end
                    elseif current_axis(2)=='2'
                        A3=cross(R(:,:,3),R(:,:,1),2); % y=zXx
                        R(:,:,2)=A3./(sqrt(sum(A3.^2,2))*[1 1 1]);
                        if current_axis(3)=='1'
                            A4=cross(R(:,:,2),R(:,:,3),2); % x=yXz
                            R(:,:,1)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                        else
                            A4=cross(R(:,:,1),R(:,:,2),2); % z=xXy
                            R(:,:,3)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                        end
                    else
                        A3=cross(R(:,:,1),R(:,:,2),2);
                        R(:,:,3)=A3./(sqrt(sum(A3.^2,2))*[1 1 1]); % z=xXy
                        if current_axis(3)=='1'
```

```
                        A4=cross(R(:,:,2),R(:,:,3),2); % x=yXz
                        R(:,:,1)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                    else
                        A4=cross(R(:,:,3),R(:,:,2),2); % y=zXx
                        R(:,:,2)=A4./(sqrt(sum(A4.^2,2))*[1 1 1]);
                    end
                end
                %re-arrange to a 3x3xn matrix of n rotation matrices
                R=permute(R,[3,2,1]);

                %calculate Segment COM displacement
                LDQ0=QLD(R,SEG_COM(:,:,m2),SM(:,:,1,m2));

                %calculate COM
                COM0=COM0+LDQ0(:,2:4).*SEGI(m2,1);

                %save R for second loop (so no need to repeat
                ALL_R(:,:,:,m2)=R;

            end

            %calculate whole body COM (temp for adjustment)
            temp_COM=COM0/sum(SEGI(:,1));

            %make adjustments to COM based on mean COP
            adjust=mean(temp_COM(:,1:2))-nanmean(FP(:,1:2,m));
            if trial_type==2
                adjust(1)=-adjust(1);
            end

            COM_C=adjust/(sum(SEGI(15:18,1))/sum(SEGI(:,1)));
            SEG_COM(:,1,15:18)=SEG_COM(:,1,15:18)+COM_C(1);
            SEG_COM(:,2,15:18)=SEG_COM(:,2,15:18)+COM_C(2);

            %note changes for future reference
            ALL_adjust(m,1:4)=[adjust,COM_C];

%==========================================================================
% KINETICS
%==========================================================================
            COM1=zeros(size(SM,1),3);
            for m2=1:size(SEG_COM,3) %SEGMENTS
                disp(['Running segment ',num2str(m2)])
                %calculate joint moments based on wrenches
                %[] = wrench(R,hz,I,COM,PROX,DIST,W0)
                if m2==1    %Left Hand
                    if trial_type==2 %handstand trial [in contact with
the ground]
                        [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),FP2(1:last_frame,1:3,m),FP2(1:last_frame,4:9,m));
                    else %standing trial [free segment]
                        [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                    end
                elseif m2==5    %Left Foot
                    if trial_type==2 %handstand trial [free segment]
```

```
                            [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                        else %standing trial [in contact with the ground]
                            if nanmean(FP1(1:s,6,m)) < 50   %foot on force
plate
                                [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1]
=
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),FP1(1:last_frame,1:3,m),FP1(1:last_frame,4:9,m));
                            else
                                [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1]
=
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                            end
                        end
                    elseif m2==8    %Right Hand
                        if trial_type==2 %handstand trial [in contact with
the ground]
                            [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),FP1(1:last_frame,1:3,m),FP1(1:last_frame,4:9,m));
                        else %standing trial [free segment]
                            [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                        end
                    elseif m2==12   %Right Foot
                        if trial_type==2 %handstand trial [free segment]
                            [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                        else %standing trial [in contact with the ground]
                            if nanmean(FP2(1:s,6,m)) < 50   %foot on force
plate
                                [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1]
=
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),FP2(1:last_frame,1:3,m),FP2(1:last_frame,4:9,m));
                            else    %foot in air (single leg)
                                [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1]
=
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2));
                            end
                        end
                    elseif m2 == 15 %pelvis (combine hips)
                        tempDIS=SM(:,:,1,7);            %left hip
                        tempDIS(:,:,2)=SM(:,:,1,14);    %right hip
                        tempW=WR(1:size(SM,1),:,7,m);               %left
hip
                        tempW(:,:,2)=WR(1:size(SM,1),:,14,m);       %right
hip
                        [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),tempDIS,tempW);
                    elseif m2 == 18 %Head (combine shoulders and thorax)
                        tempDIS=SM(:,:,1,4);            %left shoulder
                        tempDIS(:,:,2)=SM(:,:,1,11);    %right shoulder
                        tempDIS(:,:,3)=SM(:,:,1,17);    %thorax (C7)
```

```
                        tempW=WR(1:size(SM,1),:,4,m);               %left
shoulder
                        tempW(:,:,2)=WR(1:size(SM,1),:,11,m);       %right
shoulder
                        tempW(:,:,3)=WR(1:size(SM,1),:,17,m);       %thorax
(wrench)
                        [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),tempDIS,tempW);
                    else
                        [W1,W2,AVQ1,AAQ1,LDQ1,LVQ1,LAQ1,PQ1,dH,dH1] =
wrench(ALL_R(:,:,:,m2),hz,[SEGI(m2,1),SEGI(m2,4:6)],SEG_COM(:,:,m2),SM(:,:,
1,m2),SM(:,:,1,m2-1),WR(1:size(W1,1),:,m2-1,m));
                    end

                    %Store proximal joint centre and quaternion
                    PQ(1:last_frame,:,m2)=PQ1;

                    %Store all calculated quaternions
                    ALLQ(1:size(AVQ1,1),:,1,m2,m)=AVQ1;     %segment angular
velocities
                    ALLQ(1:size(AVQ1,1),:,2,m2,m)=AAQ1;     %segment angular
accelerations
                    ALLQ(1:size(AVQ1,1),:,3,m2,m)=LVQ1;     %segment COM
velocities
                    ALLQ(1:size(AVQ1,1),:,4,m2,m)=LAQ1;     %segment COM
accelerations
                    ALLQ(1:size(AVQ1,1),:,5,m2,m)=LDQ1;     %segment COM
discplacements


                    %store wrench data [Fx, Fy, Fz, Mx, My, Mz]
                    WR(1:size(W1,1),:,m2,m)=W1;

                    %calculate COM
                    COM1=COM1+LDQ1(:,2:4).*SEGI(m2,1);
                end

                COM(1:size(COM1,1),:,1,m)=COM1/sum(SEGI(:,1));

COM(1:size(COM1,1),:,2,m)=glen_diff(COM(1:size(COM1,1),:,1,m),hz);

COM(1:size(COM1,1),:,3,m)=glen_diff(COM(1:size(COM1,1),:,2,m),hz);

                ALL_adjust(m,5:6)=mean(COM(:,1:2,1,m))-mean(FP(:,1:2,m));




            catch exception2
                warning([exception2.message,' - INVERSE DYNAMICS
@',num2str(SUBJ),'/',num2str(s),'/',num2str(m)])
                log_errors{log_count}=[exception2.message,' - INVERSE
DYNAMICS - Line: ',num2str(exception2.stack (end).line),' -
',num2str(SUBJ),'/',num2str(s),'/',num2str(m)];
            log_count=log_count+1;
            end
        end
```

```
        %free up memory where possible
        clear MARKERS Adata ALLQ ALL_R Fdata Mdata PQ LAQ1 LDQ1 LDQ0 LVQ1
LAQ1 SM
%-------------------------------------------------------------------------
% NOTE: The wrench is applied to the joint/segment by the preceeding
%       segment; this means there is an issue with following the path of
%       force from foot to hand, and you may want to negate either the arms
%       or legs and trunk [but do this at the end otherwise the head will
%       be wrong] - I've done the arms in handstand, and the legs and trunk
%       in standing
%-------------------------------------------------------------------------

        if trial_type==2
            %negate upper limb
            WR(:,:,[1:4,8:11],:)=-WR(:,:,[1:4,8:11],:);
        else
            %negate lower limb and trunk
            WR(:,:,[5:7,12:18],:)=-WR(:,:,[5:7,12:18],:);
        end

        disp([Subject,Session,' data loaded = ',num2str(toc)])

%=========================================================================
% DELAY ESTIMATES
%=========================================================================


        DELAY1=nan(trials,14);
        MOV_COR=nan(6000,6,trials);
        cross_cor=nan(trials,16);
        FULL_XCORR_R=nan(6000,24,trials);
        FULL_XCORR_D=nan(6000,24,trials);
        DELAY2=nan(trials,28);
        DELAY3=nan(trials,28);
        DELAY4=nan(trials,28);
        ALL_EMG_ACT=nan(trials,63);
        ALL_TQ_ACT=nan(trials,36);
        for m=1:trials
            if trial_type==2
                TORQUES=[WR(:,4,1,m)+WR(:,4,8,m),...     %wrist
                         WR(:,4,2,m)+WR(:,4,9,m),...     %elbow
                         WR(:,4,3,m)+WR(:,4,10,m),...    %shoulder
                         WR(:,4,7,m)+WR(:,4,14,m)];      %hip
            else
                TORQUES=[WR(:,4,5,m)+WR(:,4,12,m),...    %ankle
                         WR(:,4,6,m)+WR(:,4,13,m),...    %knee
                         WR(:,4,7,m)+WR(:,4,14,m),...    %hip
                         WR(:,4,3,m)+WR(:,4,10,m)];      %shoulder
            end
            last_frame=floor(pp(m)*hz);
            % standard: wrist/ankle vs COM
            if last_frame < size(WR,1)
                offset_hz=hz/2;
            else
                offset_hz=0;
            end

            %COM correction for moving refernce frame
            temp_COM=COM(:,:,1,m)-FP_ORIGIN(:,:,m); %don't forget velocity
correction
```

```
            temp_COM(:,:,2)=glen_diff(temp_COM,hz);

            if last_frame > 300

                [D1a]=delays2(TORQUES(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                % extra 1
                [D1c]=delays2(TORQUES(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);

                %DELAY1(m,:)=[D1a,D1b,D1c];
                DELAY1(m,:)=[D1a,D1c];
            end



            mass=subject_mass;
            height=nanmean(COM(1:100,3,1,m))-nanmean(FP1(:,3,m));

            %Torque movement units (normalise to mass * h.^2)
            TQ_ACT=nan(3,12);
            for TQ=1:3
                [LTQ,MTQ,STQ] = MC(TORQUES(:,TQ),hz);
                TQ_ACT(TQ,:)=[(size(LTQ,1)-1)/pp(m),nanmean(LTQ(1:end-
1,3:4),1)/(mass*height.^2),nanmean(LTQ(1:end-1,5),1),...
                              (size(MTQ,1)-1)/pp(m),nanmean(MTQ(1:end-
1,3:4),1)/(mass*height.^2),nanmean(MTQ(1:end-1,5),1),...
                              (size(STQ,1)-1)/pp(m),nanmean(STQ(1:end-
1,3:4),1)/(mass*height.^2),nanmean(STQ(1:end-1,5),1)];
            end
            ALL_TQ_ACT(m,:)=[TQ_ACT(1,:),TQ_ACT(2,:),TQ_ACT(3,:)];


            %load MVC trials
            if ~exist('MVC','var')
                mvcfile=[dir,Subject,Session,'MVC_01.txt'];
%                 mvcfile=[dir,Subject,'MVC_01.txt'];
                mvc=importdata(mvcfile);
                mvcemg=abs(Filtmat(1/2000,[20
500],4,mvc.data(:,14:29),'bandpass'));
                MVC=max(Filtmat(1/2000,10,4,mvcemg));

                mvcfile=[dir,Subject,Session,'MVC_02.txt'];
%                 mvcfile=[dir,Subject,'MVC_02.txt'];
                mvc=importdata(mvcfile);
                mvcemg=abs(Filtmat(1/2000,[20
500],4,mvc.data(:,14:29),'bandpass'));
                MVC(2,:)=max(Filtmat(1/2000,10,4,mvcemg));

                mvcfile=[dir,Subject,Session,'MVC_03.txt'];
%                 mvcfile=[dir,Subject,'MVC_03.txt'];
                mvc=importdata(mvcfile);
                mvcemg=abs(Filtmat(1/2000,[20
500],4,mvc.data(:,14:29),'bandpass'));
                MVC(3,:)=max(Filtmat(1/2000,10,4,mvcemg));

                mvcfile=[dir,Subject,Session,'ST_MVC_01.txt'];
```

```
%                 mvcfile=[dir,Subject,'ST_MVC_01.txt'];
                mvc=importdata(mvcfile);
                mvcemg=abs(Filtmat(1/2000,[20
500],4,mvc.data(:,14:29),'bandpass'));
                ST_MVC=max(Filtmat(1/2000,10,4,mvcemg));

                mvcfile=[dir,Subject,Session,'ST_MVC_02.txt'];
%                 mvcfile=[dir,Subject,'ST_MVC_02.txt'];
                mvc=importdata(mvcfile);
                mvcemg=abs(Filtmat(1/2000,[20
500],4,mvc.data(:,14:29),'bandpass'));
                ST_MVC(2,:)=max(Filtmat(1/2000,10,4,mvcemg));

                MVC=max(MVC,[],1);
                ST_MVC=max(ST_MVC,[],1);
            end


            MVC=max(MVC,[],1);
            ST_MVC=max(ST_MVC,[],1);
            %now EMG
            if trial_type==1

EMG=Filtmat(1/hz,10,4,ALL_EMG(1:last_frame,:,m))./(ones(last_frame,1)*ST_MV
C);
            else

EMG=Filtmat(1/hz,10,4,ALL_EMG(1:last_frame,:,m))./(ones(last_frame,1)*MVC);
            end



            %movement units

            %just look at sensors 1-4 (so same for handstand and standing)
            % 1 & 3 = Wrist Flex/TibAnt;
            % 2 & 4 = Wrist Ext/Gast;
            EMG_ACT=nan(7,9);
            for E=1:4
                [Lburst,Mburst,Sburst] = MC(EMG(:,E),hz);
                EMG_ACT(E,:)=[(size(Lburst,1)-
1)/pp(m),nanmean(Lburst(1:end-1,2),1),nanmean(Lburst(1:end-1,5),1),...
                              (size(Mburst,1)-
1)/pp(m),nanmean(Mburst(1:end-1,2),1),nanmean(Mburst(1:end-1,5),1),...
                              (size(Sburst,1)-
1)/pp(m),nanmean(Sburst(1:end-1,2),1),nanmean(Sburst(1:end-1,5),1)];

            end

            %combine EMG
            temp_EMG=EMG(:,1)+EMG(:,2)-EMG(:,3)-EMG(:,4);
            temp_EMG1=EMG(:,1)+EMG(:,2);
            temp_EMG2=EMG(:,3)+EMG(:,4);

            %check activity for this lot
            [Lburst,Mburst,Sburst] = MC(temp_EMG(:,1),hz);
            EMG_ACT(5,:)=[(size(Lburst,1)-1)/pp(m),nanmean(Lburst(1:end-
1,2),1),nanmean(Lburst(1:end-1,5),1),...
```

```
                                (size(Mburst,1)-
1)/pp(m),nanmean(Mburst(1:end-1,2),1),nanmean(Mburst(1:end-1,5),1),...
                                (size(Sburst,1)-
1)/pp(m),nanmean(Sburst(1:end-1,2),1),nanmean(Sburst(1:end-1,5),1)];

            [Lburst1,Mburst1,Sburst1] = MC(temp_EMG1(:,1),hz);
            EMG_ACT(6,:)=[(size(Lburst1,1)-1)/pp(m),nanmean(Lburst1(1:end-
1,2),1),nanmean(Lburst1(1:end-1,5),1),...
                                (size(Mburst1,1)-
1)/pp(m),nanmean(Mburst1(1:end-1,2),1),nanmean(Mburst1(1:end-1,5),1),...
                                (size(Sburst1,1)-
1)/pp(m),nanmean(Sburst1(1:end-1,2),1),nanmean(Sburst1(1:end-1,5),1)];

            [Lburst2,Mburst2,Sburst2] = MC(temp_EMG2(:,1),hz);
            EMG_ACT(7,:)=[(size(Lburst2,1)-1)/pp(m),nanmean(Lburst2(1:end-
1,2),1),nanmean(Lburst2(1:end-1,5),1),...
                                (size(Mburst2,1)-
1)/pp(m),nanmean(Mburst2(1:end-1,2),1),nanmean(Mburst2(1:end-1,5),1),...
                                (size(Sburst2,1)-
1)/pp(m),nanmean(Sburst2(1:end-1,2),1),nanmean(Sburst2(1:end-1,5),1)];


ALL_EMG_ACT(m,:)=[EMG_ACT(1,:),EMG_ACT(2,:),EMG_ACT(3,:),EMG_ACT(4,:),EMG_A
CT(5,:),EMG_ACT(6,:),EMG_ACT(7,:)];


            %Cross correlations of EMG to COM [torque to COM?)

[ef1,er1]=delay_old(temp_EMG(1:last_frame,1),temp_COM(1:last_frame,2,1),hz,
0,1);

[ef1a,er1a]=delay_old(TORQUES(1:last_frame,1),temp_COM(1:last_frame,2,1),hz
,0,1);

            %Cross correlations of EMG to Torque

[ef2,er2]=delay_old(temp_EMG(1:last_frame,1),TORQUES(1:last_frame,1),hz,0,1
);

[ef3,er3]=delay_old(temp_EMG1(1:last_frame,1),TORQUES(1:last_frame,1),hz,0,
1);

[ef4,er4]=delay_old(temp_EMG2(1:last_frame,1),TORQUES(1:last_frame,1),hz,0,
1);

            %xcorr for segment torque delays

[f1,r1]=delay_old(TORQUES(1:last_frame,1),TORQUES(1:last_frame,2),hz,0,1);
%ankle/wrist to knee/shoulder

[f2,r2]=delay_old(TORQUES(1:last_frame,1),TORQUES(1:last_frame,3),hz,0,1);
%ankle/wrist to hip

[f3,r3]=delay_old(TORQUES(1:last_frame,2),TORQUES(1:last_frame,3),hz,0,1);
%knee/shoulder to hip

            %store cross correlations
%
cross_cor(m,:)=[ef1(1),er1(1),ef1a(1),er1a(1),ef2(1),er2(1),ef3(1),er3(1),e
f4(1),er4(1),f1(1),r1(1),f2(1),r2(1),f3(1),r3(1)];
```

```
            cross_cor(m,:)=[ef1(2),er1(2),ef1a(2),er1a(2),ef2(2),er2(2),...

ef3(1),er3(1),ef4(1),er4(1),f1(1),r1(1),f2(1),r2(1),f3(1),r3(1)];

            %corr for segment torque strategy using a moving window to
            %determine the strategy used (without delays)

[~,mr1]=delay_old(TORQUES(1:last_frame,1),TORQUES(1:last_frame,2),hz,1,0,5)
; %ankle/wrist to knee/elbow

[~,mr2]=delay_old(TORQUES(1:last_frame,1),TORQUES(1:last_frame,3),hz,1,0,5)
; %ankle/wrist to hip/shoulder

[~,mr3]=delay_old(TORQUES(1:last_frame,1),TORQUES(1:last_frame,4),hz,1,0,5)
; %ankle/wrist to shoulder/hip

[~,mr4]=delay_old(TORQUES(1:last_frame,2),TORQUES(1:last_frame,3),hz,1,0,5)
; %knee/elbow to hip/shoulder

[~,mr5]=delay_old(TORQUES(1:last_frame,2),TORQUES(1:last_frame,4),hz,1,0,5)
; %knee/elbow to shoulder/hip

[~,mr6]=delay_old(TORQUES(1:last_frame,3),TORQUES(1:last_frame,4),hz,1,0,5)
; %hip/shoulder to shoulder/hip

            %Store moving correlations

MOV_COR(1:size(mr1,1),:,m)=[mr1(:,1),mr2(:,1),mr3(:,1),mr4(:,1),mr5(:,1),mr
6(:,1)];
            %Store time, joint torques, COP, and COM motion for future
reference
            TORQ_COM(1:last_frame,:,m,TYP,SUBJ)=[((1:last_frame)'-
platform_trial(m))/hz,...

TORQUES(1:last_frame,1:4),FP(1:last_frame,2,m),permute(COM(1:last_frame,2,1
:2,m),[1,3,2])];

            if trial_type==2    %handstand (wrist, elbow, shoulder, hip)
                f=find(isnan(MOV_COR(:,1,m)),1)-1;
                TEMP1=MOV_COR(1:f,[1,4,6],m)>0;
                PERC_1(m,:,TYP,SUBJ)=[1,f,DIR(m),...
                     sum([sum(TEMP1,2)==3,...                %wrist strategy
                    (sum(TEMP1,2)==2) & TEMP1(:,1)==0,...    %elbow strategy
                    (sum(TEMP1,2)==2) & TEMP1(:,2)==0,...    %shoulder
strategy
                    (sum(TEMP1,2)==2) & TEMP1(:,3)==0,...    %hip strategy
                    (sum(TEMP1,2)<2)])/f*100];               %mixed strategy

                %normalise to time by only looking at +/- 1 second after
                %perturbation
                EF=min([f,platform_trial(m)+hz]);
                SF=max([1,platform_trial(m)-hz]);
                TEMP2=MOV_COR(SF:EF,[1,4,6],m)>0;
                PERC_2(m,:,TYP,SUBJ)=[SF,EF,DIR(m),...
                     sum([sum(TEMP2,2)==3,...                %wrist strategy
                    (sum(TEMP2,2)==2) & TEMP2(:,1)==0,...    %elbow strategy
                    (sum(TEMP2,2)==2) & TEMP2(:,2)==0,...    %shoulder
strategy
                    (sum(TEMP2,2)==2) & TEMP2(:,3)==0,...    %hip strategy
```

```
                    (sum(TEMP2,2)<2)])/(EF-SF+1)*100];              %mixed
strategy

                if SF>1
                    %get balance until above starts
                    TEMP3=MOV_COR(1:SF,[1,4,6],m)>0;
                    PERC_3(m,:,TYP,SUBJ)=[1,SF,DIR(m),...
                         sum([sum(TEMP3,2)==3,...                %wrist
strategy
                        (sum(TEMP3,2)==2) & TEMP3(:,1)==0,...    %elbow
strategy
                        (sum(TEMP3,2)==2) & TEMP3(:,2)==0,...    %shoulder
strategy
                        (sum(TEMP3,2)==2) & TEMP3(:,3)==0,...    %hip
strategy
                        (sum(TEMP3,2)<2)])/SF*100];               %mixed
strategy
                end



            else    %standing (ankle, knee, hip)
                f=find(isnan(MOV_COR(:,1,m)),1)-1;
                TEMP1=MOV_COR(1:f,[1,4],m)>0;
                PERC_1(m,1:7,TYP,SUBJ)=[1,f,DIR(m),...
                     sum([sum(TEMP1,2)==2,...                %ankle strategy
                    (sum(TEMP1,2)==1) & TEMP1(:,1)==0,...    %knee strategy
                    (sum(TEMP1,2)==1) & TEMP1(:,2)==0,...    %hip strategy
                    (sum(TEMP1,2)<1)])/f*100];               %mixed strategy


                %normalise to time by only looking at +/- 1 second after
                %perturbation
                EF=min([f,platform_trial(m)+hz]);
                SF=max([1,platform_trial(m)-hz]);
                TEMP2=MOV_COR(SF:EF,[1,4],m)>0;
                PERC_2(m,1:7,TYP,SUBJ)=[SF,EF,DIR(m),...
                     sum([sum(TEMP2,2)==2,...                %ankle strategy
                    (sum(TEMP2,2)==1) & TEMP2(:,1)==0,...    %knee strategy
                    (sum(TEMP2,2)==1) & TEMP2(:,2)==0,...    %hip strategy
                    (sum(TEMP2,2)<1)])/(EF-SF+1)*100];              %mixed
strategy

                if SF>1
                    %get balance until above starts
                    TEMP3=MOV_COR(1:SF,[1,4],m)>0;
                    PERC_3(m,1:7,TYP,SUBJ)=[1,SF,DIR(m),...
                         sum([sum(TEMP3,2)==2,...                %ankle
strategy
                        (sum(TEMP3,2)==1) & TEMP3(:,1)==0,...    %knee
strategy
                        (sum(TEMP3,2)==1) & TEMP3(:,2)==0,...    %hip
strategy
                        (sum(TEMP3,2)<1)])/SF*100];               %mixed
strategy
                end

            end
```

```
            %DELAY of EMG to COM
            if last_frame > 300
                [EMG_D1a]=delays2(temp_EMG(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D1c]=delays2(temp_EMG(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %just in case
                [EMG_D2a]=delays2(-temp_EMG(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D2c]=delays2(-temp_EMG(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %DELAY1(m,:)=[D1a,D1b,D1c];
                DELAY2(m,:)=[EMG_D1a,EMG_D1c,EMG_D2a,EMG_D2c];
            end

            if last_frame > 300
                [EMG_D1a]=delays2(temp_EMG1(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D1c]=delays2(temp_EMG1(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %just in case
                [EMG_D2a]=delays2(-temp_EMG1(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D2c]=delays2(-temp_EMG1(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %DELAY1(m,:)=[D1a,D1b,D1c];
                DELAY3(m,:)=[EMG_D1a,EMG_D1c,EMG_D2a,EMG_D2c];
            end

            if last_frame > 300
                [EMG_D1a]=delays2(temp_EMG2(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D1c]=delays2(temp_EMG2(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %just in case
                [EMG_D2a]=delays2(-temp_EMG2(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,2)],hz,5,1,0,0,0);
                [EMG_D2c]=delays2(-temp_EMG2(1:last_frame-
offset_hz,1),[temp_COM(1:last_frame-offset_hz,2,1),temp_COM(1:last_frame-
offset_hz,2,1),temp_COM(1:last_frame-offset_hz,2,2)],hz,5,1,1,0,0);
                %DELAY1(m,:)=[D1a,D1b,D1c];
                DELAY4(m,:)=[EMG_D1a,EMG_D1c,EMG_D2a,EMG_D2c];
            end


            disp(['Analysis ',num2str(m),' = ',num2str(toc)])
        end
```

```
        %print out to excel file

        %get means and std of everthing

outputMEAN(TYP,:)=[nanmean(pp,1),nanmean(DELAY1,1),nanmean(DELAY2,1),nanmea
n(DELAY3,1),nanmean(DELAY4,1),nanmean(cross_cor,1),nanmean(ALL_TQ_ACT,1),na
nmean(ALL_EMG_ACT,1)];

outputSTD(TYP,:)=[nanstd(pp,[],1),nanstd(DELAY1,[],1),nanstd(DELAY2,[],1),n
anstd(DELAY3,[],1),nanstd(DELAY4,[],1),nanstd(cross_cor,[],1),nanstd(ALL_TQ
_ACT,[],1),nanstd(ALL_EMG_ACT,[],1)];

        %save all data

outputALL(1:m,:,TYP)=[pp(1:trials),DIR(1:trials),DELAY1,DELAY2,DELAY3,DELAY
4,cross_cor,ALL_TQ_ACT,ALL_EMG_ACT];

        ALL_MOV_COR(1:size(MOV_COR,1),:,1:trials,TYP)=MOV_COR;

%=====================END OF IF TEST (SESSION)============================
    end

    disp([Subject,'trial ',num2str(TYP),' = ',num2str(toc)])
%==============================END OF TRIAL TYPE+=========================
end

ALL_SUB_MOV_COR(1:size(ALL_MOV_COR,1),:,1:size(ALL_MOV_COR,3),:,SUBJ)=ALL_M
OV_COR;

% load mat file to save all mean and std data

% % load phd_chapter6_NEW.mat
% load paper_2b.mat
%
% MEAN_DATA(SUBJ,:,1:size(outputMEAN,1))=permute(outputMEAN,[3,2,1]);
% STD_DATA(SUBJ,:,1:size(outputSTD,1))=permute(outputSTD,[3,2,1]);
%
ALL_DATA(SUBJ,:,1:size(outputALL,1),1:size(outputALL,3))=permute(outputALL,
[4,2,1,3]);
%
% % save('phd_chapter6_NEW.mat','MEAN_DATA','STD_DATA','ALL_DATA');
% save('paper_2b.mat','HEADERS','MEAN_DATA','STD_DATA','ALL_DATA');

save('paper_2_NEW.mat','ALL_SUB_MOV_COR','TORQ_COM','PERC_1','PERC_2','PERC
_3');

% xlswrite([dir,'NEW Statics.xls'],outputALL(:,:,1),['Subject_',sub]);
disp([Subject,Session,' = ',num2str(toc)])

%==============================END OF SESSION==============================
end

end

%==============================PLOTS=======================================

% time1=(1/hz:1/hz:pp(1))';
% time2=(1/2000:1/2000:pp(1))';
```

```
% plot(time2,RAW_EMG(:,1)+RAW_EMG(:,2))
% hold on
% plot(time2,-RAW_EMG(:,3)-RAW_EMG(:,4))
```