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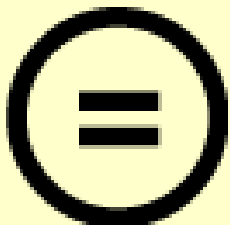
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The Biomechanical Design and Analysis of Gymnastics Training Equipment

by

Emma Rosamond

A Doctoral Thesis

**Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of Loughborough University**

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Abstract

Training aids can play an important role in the training of athletes, but only if they assist in the learning of correct technique. The design of a training aid differs considerably from the design of other products because it is crucial that the mechanisms used in learning a skill must be taken into consideration. Research has shown that this can be achieved by: encouraging specific motor skills, providing feedback, providing support in a safe environment, permitting repetition, permitting progressive learning, or by providing some combination of these. For this to be possible an in-depth understanding of the biomechanical requirements of the sporting activity is essential.

A study was carried out to determine the fundamental requirements of a training aid, and to then design and build two working prototype gymnastics training aids. Elite training sessions were observed and High Performance coaches were interviewed to establish the skills that required a training aid and the customer requirements for such a device. On the basis of this information two contrasting gymnastics skills were chosen. The first was a handstand on the rings, a complex motor control skill requiring the gymnast to balance on two moving pendulums, requested by 100% of the coaches interviewed. The second skill was a backward handspring, often the first backward dynamic skill most gymnasts will learn, requested by 89% of the coaches interviewed. The training aids were required to simplify the learning of the skill, whilst still utilising correct technique. The backward handspring aid was also required to effectively support the gymnast but not obstruct a good performance.

A biomechanical analysis of each skill was carried out in order to inform the design of suitable training aids. The aids were designed and manufactured in accordance with British Standards, and were then biomechanically assessed to ensure that they correctly aided the learning of the skills. In order to assess the aids: displacement, force and muscle activation data were collected and were used to compare the gymnastics skills with and without the aids. The data showed that the training aids replicated the correct biomechanical requirements of the actual skills: the handstand aid was shown to utilise the same control mechanism as was observed on the rings, and the backward handspring aid permitted a unobstructed good performance and assisted in the learning of the skills with correct technique. Both aids were also demonstrated to out-perform any of the existing training aids.

Key words: training aids, gymnastics, backward handspring, rings, handstand, equipment design.

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Dedication

*To Gareth,
and my family*

Table of Contents

Abstract	i
Acknowledgements	ii
Dedication	iii
Table of Contents	iv
List of Figures and Tables	x
1 Introduction	1
1.1 Introduction	1
1.2 Statement of purpose	3
1.3 Research question	3
1.4 Research objectives	3
1.5 Scope of research	4
1.6 Organisation of chapters	4
2 Literature Review	8
2.1 Introduction	8
2.1.1 Overview of gymnastics research	8
2.1.2 Overview of training aid research	9
2.2 Equipment design and engineering	10
2.2.1 Biomechanical approach to equipment design	10
2.2.2 Sports engineering and design	11
2.2.3 Material considerations	13
2.2.4 Safety considerations	14
2.2.5 Design methodology	16
2.2.6 Design processes	17
2.2.7 British Standards	19
2.3 Experimental and theoretical research	20
2.3.1 Experiment design	20
2.3.2 Error	24
2.3.3 Anthropometric data	25
2.3.4 Ethical Clearance	26
2.4 Learning, growing, and motor control	26

2.4.1	Skill acquisition	26
2.4.2	Reaction time and anticipation	28
2.4.3	Human growth	29
2.5	Chapter summary	30
3	Skill Selection and Preliminary Design Considerations	31
3.1	Introduction	31
3.1.1	Initial research of gymnastics skills	32
3.1.2	Handstand on the rings – skill information	34
3.1.3	Backward handspring – skill information	35
3.2	Requirements	35
3.3	Literature review of the chosen skills	38
3.3.1	Handstand on the rings	38
3.3.2	Backward handspring	46
3.4	Summary of requirements for a generic training aid	57
3.4.1	Design methodology	61
3.4.2	Customer requirements	61
3.4.3	Customer analysis	65
3.4.4	Quality function deployment	66
3.5	Chapter summary	69
4	Rings Handstand Analysis	70
4.1	Mechanical analysis of the handstand on rings	70
4.1.1	Introduction	70
4.1.2	Theory	71
4.1.3	Theoretical model assessment	82
4.2	Data collection	87
4.2.1	Introduction	87
4.2.2	Pre testing	87
4.2.3	Pilot study	99
4.2.4	Rings data collection	101
4.3	Data analysis	103
4.3.1	Force data	104
4.3.2	Displacement data	105
4.3.3	EMG data	108

4.3.4	Summary and design considerations	110
5	Rings Handstand Training Aid Design and Manufacture	112
5.1	Introduction	112
5.2	Design path for a rings handstand training aid	112
5.3	Requirement tree and product design specification	114
5.4	Design process	114
5.4.1	Design data from testing	114
5.4.2	Preliminary design concepts	115
5.4.3	Analysing conceptual work	115
5.5	Design calculations	118
5.5.1	Linear guide specification	118
5.5.2	Linear guide calculations	119
5.5.3	Top foam calculations and testing	121
5.6	Detailed design	124
5.6.1	Complete concept	124
5.6.2	Failure analysis	128
5.6.3	British Standards requirements	131
5.6.4	Final design	131
5.7	Chapter summary	132
6	Handstand Training Aid Analysis	133
6.1	Introduction	133
6.2	Safety testing	133
6.2.1	British Standards safety testing	133
6.2.2	Further safety testing	135
6.2.3	Risk assessment	135
6.3	Data collection	139
6.3.1	Experimental set up	140
6.3.2	Rings and training aid data collection	144
6.4	Data analysis - handstand comparison	147
6.4.1	Muscle data	147
6.4.2	Handstand comparison - EMG results	147
6.4.3	Force and strain data	153
6.4.4	Handstand comparison - force results	155

6.4.5	Motion analysis data	156
6.4.6	Handstand comparison – motion analysis results	157
6.4.7	Summary of comparison	162
6.5	Training aid details	163
6.5.1	The handstand swing	163
6.5.2	The handstand bowls	163
6.5.3	The handstand rails	164
6.6	Data analysis - training aid comparison	165
6.6.1	Muscle data	165
6.6.2	Training aid comparison - EMG results	166
6.6.3	Force data	170
6.6.4	Training aid comparison - force results	170
6.6.5	Motion analysis data	173
6.6.6	Training aid comparison – motion analysis results	174
6.6.7	Summary of Comparison	184
6.6.8	Coach and gymnast feedback	185
6.7	Chapter summary	186
7	Backward Handspring Analysis	188
7.1	Mechanical analysis of the backward handspring	188
7.1.1	Introduction	188
7.1.2	Theory	188
7.2	Data collection	194
7.2.1	Introduction	194
7.2.2	Pre-testing	195
7.2.3	Pilot study	197
7.2.4	Backward handspring data collection	200
7.3	Data analysis	202
7.3.1	Statistical analysis of hypothesised relationships	202
7.3.2	Design considerations	205
8	Backward Handspring Training Aid Design and Manufacture	206
8.1	Introduction	206
8.2	Design path for a backward handspring training aid	206
8.3	Product design specification	208

8.4	Design process	208
8.4.1	Design data from testing	208
8.4.2	Preliminary design concepts	211
8.4.3	Design considerations	214
8.4.4	Considering the free volume	215
8.5	Detailed design	218
8.5.1	The metal structure	218
8.5.2	The support section and upright column	221
8.5.3	Failure analysis	227
8.5.4	Design of the seat section and post padding	235
8.5.5	British Standards requirements	236
8.5.6	Final design	236
8.6	Chapter summary	237
9	Backward handspring Training Aid Analysis	238
9.1	Introduction	238
9.2	Safety testing	238
9.2.1	British Standards safety testing	238
9.2.2	Further impact and stability testing	240
9.2.3	Primary collision analysis	243
9.2.4	Risk assessment	243
9.2.5	Initial gymnast - equipment interface analysis	248
9.3	Pilot study	248
9.3.1	Vicon data collection	248
9.4	Data collection	250
9.4.1	Further collision analysis	250
9.4.2	Gymnast skill-preparation analysis	251
9.4.3	Main testing	251
9.5	Data analysis	252
9.5.1	Methodology	252
9.5.2	Performance parameter comparisons	253
9.5.3	Joint angle comparisons	254
9.5.4	Discussion of results	255
9.5.5	Conclusion of findings	258
9.5.6	Gymnast and coach feedback	259

9.5.7	Design modifications	261
9.6	Individual learning experience	263
9.6.1	Skill improvement	263
9.6.2	Skill learnt on the training aid	265
9.7	Chapter summary	266
10	Summary and Conclusion	267
10.1	Introduction	267
10.2	Summary of evidence	267
10.3	Limitations and progressive developments	275
10.4	Relevance and justification	275
10.5	Further research	276
10.6	Conclusion	278
	References	279
	Bibliography	294
	Appendices	299
A:	3-Dimensional model drawings of the training aids	300
B:	Full requirement trees for the training aids	306
C:	Product design specifications of the training aids	311
D:	Model of a handstand on a frictionless surface (Chapter 4)	320
E:	Joint centre data for handstand trials (Chapter 6)	331
F:	Correlation plots for performance parameters (Chapter 7)	337
G:	Backward handspring data (Chapter 9)	341

List of Figures and Tables

2 Literature Review

Figure 2 1: Equipment design between the goals of performance, marketing interest and injury prevention.	12
Figure 2 2: The design process as a linear activity.	17
Figure 2 3: The relationship of the components of the product design process.	18
Figure 2 4: The theory-experiment cycle of scientific method.	21
Figure 2 5: A suggested classification of skilled tasks.	28
Table 2 1: Lengths of body segments as a percentage of standing height	29

3 Selection of Gymnastics Skills, and Preliminary Design Considerations

Figure 3-1: Design process for a gymnastics training aid.	32
Figure 3-2: Survey results of problems with existing rings handstand training aids.	36
Figure 3-3: Survey results of problems with backward handspring existing training aids.	37
Figure 3-4: The bent body press to handstand.	39
Figure 3-5: A representation of a gymnast in a handstand.	40
Figure 3-6: The basic anatomical position.	42
Figure 3-7: Janssen Fritsen Handstand swing.	43
Figure 3-8: Janssen Fritsen Handstand Bowl.	43
Figure 3-9: Janssen Fritsen Mini Bowls.	44
Figure 3-10: Janssen Fritsen Rings for Parallel Bars.	44
Figure 3-11: Rings handstand with a supportive strap.	45
Figure 3-12: (a) Floater backward handspring, (b) Accelerator backward handspring.	47
Figure 3-13: A foam block backward handspring training aid.	48
Figure 3-14: Falling Phase of the backward handspring.	50
Figure 3-15: Angles and velocities of the backward handspring.	51
Figure 3-16: Poor techniques of the backward handspring: (a) Knees 'roll' forward (b) Lack of rotation on landing. (1993).	52

Figure 3-17: Vaulting board incline training device.	53
Figure 3-18: Foam incline training aid.	53
Figure 3-19: $\frac{3}{4}$ Foam cylinder training aid.	54
Figure 3-20: Foam cylinder training aid.	54
Figure 3-21: Assorted gymnastics harnesses.	55
Figure 3-22: Top level of the design path for a gymnastics training aid	57
Figure 3-23: (a) Design path for the development of a conditioning training aid.	58
Figure 3-23: (b) Design path for the development of a training aid to teach a specific component of a skill.	59
Figure 3 23: (c) Design path for the development of a training aid for a full skill.	60
Figure 3-24: Customer requirement tree for the rings handstand training aid.	63
Figure 3-25: Customer requirement tree for the backward handspring training aid.	64
Figure 3-26: QFD-House of quality for the rings handstand training aid.	67
Figure 3-27: QFD-House of quality for the backward handspring training aid.	68
Table 3-1: Competitor analysis of existing rings handstand training aids	65
Table 3-2: Competitor analysis of existing backward handspring training aids	66
4 Handstand Analysis	
Figure 4-1: Curvature of rings motion explanation.	71
Figure 4-2: Model of the handstand on a surface free to move horizontally.	72
Figure 4-3: The range of values of p/dk which correspond to stable control.	75
Figure 4-4: Schematic of the upper body segment of the gymnast.	77
Figure 4-5: Schematic of segment B of the 2 segment handstand model.	78
Figure 4-6: Schematic of segment A of the 2 segment handstand model.	80
Figure 4-7: Comparison of the rings model and the training aid model	83
Figure 4-8: Pythagoras triangle representing movement of the rings model	85
Figure 4-9: A load cell.	88
Figure 4-10: Amplifier and power supply connected to the PC.	89
Figure 4-11: Experimental set up for load cell calibration and testing.	89
Figure 4-12: Graph of load cell calibration loading pattern.	90
Figure 4-13: Graph of reduced loading load cell calibration loading pattern (35 kg).	91
Figure 4-14: A simple pendulum: (a) stationary (b) top of the swing	92

(c) bottom of the swing.	
Figure 4-15: The rings scenario.	92
Figure 4-16: Pythagoras description of ring location in x-y plane.	93
Figure 4-17: Series of springs within the rings apparatus.	94
Figure 4-18: Rings loading on full rings frame.	95
Figure 4-19: Vicon M2 camera.	96
Figure 4-20: Static calibration frame.	96
Figure 4-21: Rings Vicon capture volume.	97
Figure 4-22: Example of raw EMG data.	98
Figure 4-23: The anterior and posterior view of the superficial skeletal muscles	99
Figure 4-24: Position of Vicon cameras around the gymnastics centre balcony.	100
Figure 4-25: Gymnast S with EMG electrodes and Vicon markers.	102
Figure 4-26: Time history for handstand 3, left wrist raw and filtered strain data	106
Figure 4-27: Time history for handstand 3, left wrist raw and filtered x-displacement data.	106
Figure 4-28: Time history for handstand 4, raw and filtered x-displacement data.	106
Figure 4-29: Time history for wrist x-displacement.	107
Figure 4-30: Time history for wrist y-displacement.	107
Figure 4-31: Raw EMG signal for handstand trial 2.	108
Figure 4.32: Processed EMG signal for handstand trial 2.	109
Figure 4-33: Raw EMG signal for handstand trial 4.	109
Figure 4-34: Processed EMG signal for handstand trial 4.	110
Table 4-1: Data from Yeadon's (1990) inertia model, for gymnast S	77
Table 4-2: Peak forces from the four handstand trials	104
5 Rings Handstand Training Aid Design and Manufacture	
Figure 5-1: Design path for a training aid to help teach a handstand on the rings.	113
Figure 5-2: Morphology chart for the rings handstand training aid.	116
Figure 5-3: Initial full concept of the rings handstand training aid.	117
Figure 5-4: Type SHS linear guide loads (THK General catalogue).	119
Figure 5-5: Relationship between imposed load ratio and friction coefficient.	119
Figure 5-6: Permissible moments for THK slider blocks.	120
Figure 5-7: Critical damped response.	122

Figure 5-8: Limitation to rail layout.	124
Figure 5-9: Dimensional set-up for the bottom set of linear rails.	125
Figure 5-10: Dimensional set-up for the top set of linear rails.	126
Figure 5-11: Side view of base and second layer .	126
Figure 5-12: Handle assembly (not to scale).	127
Figure 5-13: Fault tree for the rings handstand training aid.	128
Figure 5-14: FMEA work sheet for the rings handstand training aid.	130
Figure 5-15: Final design concept	131

6 Handstand Training Aid Analysis

Figure 6-1: Positions of Vicon cameras around the research laboratory.	140
Figure 6-2: Locations of muscles on the human body.	142
Figure 6-3: Gymnast R with EMG electrodes and Vicon markers.	141
Figure 6-4:: Schematic of the Kistler force plate.	143
Figure 6-5: Handstand on the floor and handstand on the rings.	145
Figure 6-6: Handstand on the swing and handstand on the bowls.	146
Figure 6-7: Handstand on the designed training aid.	146
Figure 6-8: Raw EMG data for maximum isometric contractions.	148
Figure 6-9: Processed EMG data for maximum isometric contractions.	149
Figure 6-10: Processed Floor and rings wrist EMG data.	153
Figure 6-11: Strain gauge calibration equations and graph	153
Figure 6-12: 3-D co-ordinate system for cable strain.	154
Figure 6-13: Subject R, floor handstand joint centre data.	158
Figure 6-14: Subject R, rings handstand joint centre data.	158
Figure 6-15: Calculation for joint angle error.	159
Figure 6-16: Tilt angle and somersault angle description.	160
Figure 6-17: Handstand swing.	164
Figure 6-18: Handstand bowls.	164
Figure 6-19: Prototype training aid with 6-degrees of freedom.	164
Figure 6-20: Muscle activation data for all handstand trials.	166
Figure 6-21: Graph of training aid EMG data as a percentage of the rings EMG data.	167
Figure 6-22: Handstand rocker COP movement.	172

Figure 6-23: Handstand Bowls corrective actions: (a) average position of the training aid with a good handstand shape; (b) body configuration during maximum forward tilt of the training aid; (c) body configuration during maximum backward tilt of the training aid; (d) front view of average handstand position on the bowls.	173
Figure 6-24: A comparison of gymnast R's average body configurations for the best handstand position held during the trials on the three different training aids: (a) handstand on the rails; (b) handstand on the bowls; (c) handstand on the rocker.	174
Table 6-1: Risk of technology failure	136
Table 6-2: Risk of design failure	136
Table 6-3: Consequence of failure to the gymnast	137
Table 6-4: Consequence of poor technique used by the gymnast	138
Table 6-5: EMG data for floor and rings (maximum peak values)	150
Table 6-6: EMG comparison data for floor and rings	150
Table 6-7: Horizontal force data for handstand on floor and rings	155
Table 6-8: Hip and shoulder angle data for handstand on floor and rings	159
Table 6-9: Mass centre movement data	161
Table 6-10: EMG data for all trials	166
Table 6-11: EMG Graph information for each trial	170
Table 6-12: Peak force data for all trials	171
Table 6-13: Comparison of angles for all handstand trials	177
Table 6-14: Comparison of all positional data for all handstand trials	180

7 Backward Handspring Analysis

Figure 7-1: Paned image of a backward handspring.	189
Figure 7-2: Phase 1 of backward handspring: the fall.	189
Figure 7-3: Phase 2 of backward handspring: the jump.	190
Figure 7-4: Phase 3 of backward handspring: first flight.	191
Figure 7-5: Phase 4a of backward handspring: impact and rotation about the hands.	192
Figure 7-6: Phase 4b of backward handspring: arch to dish snap action.	192
Figure 7-7: Phase 4c of the backward handspring: push phase	193

Figure 7-8: Phase 5 of backward handspring: second flight.	193
Figure 7-9: Pre testing the backward handspring.	196
Figure 7-10: Calibration poles positioned within the capture volume.	197
Figure 7-11: Good igloo shape.	198
Figure 7-12: Poor igloo shape.	198
Figure 7-13: Seven performance parameters of the backward handspring.	199
Figure 7-14: Camera set up for the data collection.	200
Figure 7-15: Static stance position.	201
Figure 7-16: Bridge.	201
Figure 7-17: D-Lumbar.	201
Figure 7-18: A graph of the correlations' between standing height and leg length for performance parameter 'a'.	203
Table 7-1: R ² values for initial correlations	203
Table 7-2: Statistical analysis of performance parameters	204

8 Backward Handspring Training Aid Design and Manufacture

Figure 8-1: Design path for a training aid to help teach a backward handspring.	207
Figure 8-2: Performance parameters.	208
Figure 8-3: Concept 2 – Basic shape.	211
Figure 8-4: Concept 2 - Arc with incline.	211
Figure 8-5: Concept 3 - Adjustable arc.	211
Figure 8-6: Concept 4 - Double arc with bungee.	212
Figure 8-7: Concept 5 - Velcro adjustable arc	212
Figure 8-8: Initial design concept – ergonomically designed, adjustable igloo shape.	215
Figure 8-9: Initial concepts for size adjustment.	216
Figure 8-10: Top impact on upright column.	217
Figure 8-11: Side impact on upright column.	218
Figure 8-12: Base frame layout.	219
Figure 8-13: Justification for position of telescopic section.	220
Figure 8-14: Design of the metal frame.	221
Figure 8-15: Height locking mechanics.	221
Figure 8-16: Design of the support section.	222

Figure 8-17: Dimensions of existing components.	223
Figure 8-18: Upright section full composition.	223
Figure 8-19: Telescopic bending scenario.	224
Figure 8-20: Top telescopic section.	224
Figure 8-21: Middle telescopic section.	225
Figure 8-22: Bottom telescopic section.	225
Figure 8-23: Mohr's circle.	226
Figure 8-24: The full metal framework.	228
Figure 8-25: Fault tree for the backward handspring training aid design.	229
Figure 8-26: FMEA work sheet for the backward handspring training aid.	230
Figure 8-27: Forces involved if the top section is to be sheared away from the telescopic section.	231
Figure 8-28: Forces involved in the top section is to buckle.	232
Figure 8-29: Bending moment of profiled plate scenario.	233
Figure 8-30: Infliction of torsion onto the support section.	234
Figure 8-31: Infliction of torsion onto the telescopic section.	234
Figure 8-32: Final design concept.	237
Table 8-1: Extrapolated performance parameter data	209
Table 8-2: Division of heights into three size categories	210
Table 8-3: Dimensions for the three height settings of the training aid	210
Table 8-4: Backward handspring training aid design concept analysis	213
9 Backward handspring Training Aid Analysis	
Figure 9-1: Marker placement for Vicon data collection.	249
Figure 9-2: Results of gymnasts' feedback.	259
Figure 9-3: Methods by which the gymnasts learn their backward handsprings.	260
Figure 9-4: Data distribution describing whether or not the gymnasts found the training aid off putting.	261
Figure 9-5: Gymnast B: Initial backward handspring.	264
Figure 9-6: Gymnast B: Backward handspring after training.	264
Figure 9-7: Backward handspring of gymnast O.	265
Table 9-1: Risk of technology failure	244

Table 9-2: Risk of design failure	244
Table 9-3: Consequence of failure to the gymnast	245
Table 9-4: Consequence of poor technique used by the gymnast	246
Table 9-5: Gymnasts measured performance parameters	253
Table 9-6: Joint angles in degrees for the individual unsupported performance	254
Table 9-7: Joint angles in degrees for the individual performances over the training aid	254
Table 9-8: Differences between the joint angles for the individual unsupported performance and the performance over the training aid	255

Appendices

Figure A-1: Stage 1: Rings handstand training aid only 1 degree of freedom.	301
Figure A-2: Stage 3: Rings handstand training aid with 4 degrees of freedom, with limited sideways movement.	301
Figure A-3: Stage 4: Rings handstand training aid with 6 degrees of freedom movement.	302
Figure A-4: Stage 4: Rings handstand training aid with 6 degrees of freedom movement: Top view.	302
Figure A-5: Side view of rings handstand training aid.	303
Figure A-6: Front view of rings handstand training aid.	303
Figure A-7: Close-up of rings handstand training aid assembly.	303
Figure A-8: Backward handspring training aid frame work: small setting.	304
Figure A-9: Backward handspring training aid frame work: medium setting.	304
Figure A-10: Backward handspring training aid frame work: large setting.	304
Figure A-11: Backward handspring training with foam padding: full height (front).	305
Figure A-12: Backward handspring training aid with foam padding: full height (back).	305
Figure B-1: Top level of requirement tree.	307
Figure B-2: Sub level 1.1 of requirement tree.	307
Figure B-3: Sub level 1.2 of requirement tree.	308
Figure B-4: Sub level 1.3 of requirement tree for handstand on the rings.	308
Figure B-5: Sub level 1.4 of requirement tree.	308

Figure B-6: Sub level 1.5 of requirement tree.	309
Figure B-7: Sub level 1.3 of requirement tree for backward handspring trainer.	310
Figure D-1: Model of a handstand on a surface free to move horizontally.	321
Figure E-1: Joint centre data for floor handstand.	332
Figure E-2: Joint centre data for rings cable markers.	332
Figure E-3: Joint centre for rocker handstand.	333
Figure E-4: Joint centre data for bowls handstand.	333
Figure E-5: Joint centre data for rails 1 handstands.	334
Figure E-6: Joint centre data for rails 2 handstand.	334
Figure E-7: Joint centre data for rails 3 handstand.	335
Figure E-8: Joint centre data for rails 4 handstand.	335
Figure E-9: Joint centre data for rails 5 handstand.	336
Figure F-1: Correlation graph of performance parameter 'a'.	338
Figure F-2: Correlation graph of performance parameter 'b'.	338
Figure F-3: Correlation graph of performance parameter 'c'.	339
Figure F-4: Correlation graph of performance parameter 'd'.	339
Figure F-5: Correlation graph of performance parameter 'f'.	340
Figure F-6: Correlation graph of performance parameter 'h'.	340
Table G-1: Joint angles in degrees for the individual unsupported performances	342
Table G-2: Joint angles in degrees for the individual performances over the training aid	343
Table G-3: Differences between the joint angles for the individual unsupported performance and the performance over the training aid	344

1

Introduction

1.1 Introduction

This chapter provides an overview outlining the areas of interest within this study, and briefly describes some of the existing areas of research. The context of the investigation is established, and the purpose of the research is formalised into a single statement.

In order to provide a comprehensive framework for this study, a research question and six objectives are posed. The objectives are progressive, with solutions from one objective often providing knowledge for the subsequent objective. It is the intention of this research to satisfy the stated purpose by addressing the research question.

At present in gymnastics training aids are used to varying degrees across the world: for example in the UK they are used much less than in places such as Russia. British coaches tend to use 'set-ups' which permit the performance of a section of the skill while still utilising the relevant piece of apparatus, or in disciplines where performances involve partner work, waist harnesses and pedestals play very important roles. By far the most common way of learning a new skill is through repetition with coach support, from initial preparation through to the full performance, with differing skills requiring different levels of support and attention during the learning phase. Training aids do however exist in the UK and are available from a wide range of suppliers, but it is not entirely clear how useful they are.

Very little literature exists on gymnastic training aids, or information about their design. In fact it appears that many of the training aids in the UK have been developed through the experience of coaches and designers and hence it is expected that the quantity of scientific work behind these training aid designs is limited. If at present training aids are designed solely on the basis of experience, it might be expected that scientific knowledge may improve existing designs.

Within the disciplines of Women's Artistic Gymnastics, Men's Artistic Gymnastics, Sports Acrobatics Gymnastics and Tumbling, there are several basic key skills which must be acquired for a gymnast to become elite. Most of these skills can be divided into two categories: balance skills and dynamic skills, and training aids exist for a variety of these

skills. The physical requirements of balance and dynamic activities vary greatly from one skill to another, and hence generally so do the skill acquisition processes. Both types of skill often require several progressive learning stages. For dynamic movements most of these stages require some significant form of support so that multiple low impact repetitions can be performed in a safe environment. Balance activities generally require more basic repetitions while the body learns to engage the required motor control mechanisms for the specific skill. These basic repetitions can often be performed without a coach as the skills are inherently less dangerous than the dynamic skills.

There have been several studies carried out on gymnastics skills, such as Brewin, Yeadon and Kerwin (2000) who investigated minimising peak forces at the shoulders during backward longswings on the rings. Yeadon and Brewin (2003) optimised the performance of the backward longswing on the rings. Kriel (1996) tested a theory of takeoff mechanics for the back somersault during floor exercises, and Liu et al. (2000) completed a similar study, producing a biomechanical analysis of the backward handspring followed by a backward somersault with triple twist. Most of these papers concentrate on optimising performance through a biomechanical analysis of the gymnastics skill, but there do not appear to be many studies on gymnastics training aids, and even fewer on their design. A book containing details on several gymnastics training devices from the Soviet Union (Yevseyev, 1991) shows several sketches of various training aids, accompanied by brief descriptions of equipment applications, but contains very little or no technical and scientific information.

Studies into design methodology and strategy however do exist, such as investigations into equipment design and testing by Gros (1999). This study discussed safety considerations within design and systematic approaches to designing equipment while appreciating relationships between the goals of performance enhancement, marketing interest and injury prevention. Other studies have been more general, for example investigating design methodology, such as that of Chen, Chen and Lin (2004) into methods for processing and prioritising customer demands in variant product design, and that of Asan, Polat and Serdar (2004) into 'Integrated Methods for Designing Modular Products'.

1.2 Statement of purpose

In order to provide a focus for this study, training aids have been designed through the biomechanical analysis of specific gymnastics skills. These training aids have then been built and biomechanically tested during use to determine whether training aids such as these can assist in the learning of gymnastics skills. By addressing the research question posed, and the respective research objectives stated in the following section of this chapter it is intended that greater knowledge and understanding will be gained of the requirements for the design of a training aid to help learn gymnastics skills.

The purpose of this study is summarised as follows:

To design appropriate gymnastics training aids to assist in the progression of skill acquisition and development.

1.3 Research question

What is involved in the learning of gymnastics activities, and if training aids can assist in skill acquisition, how can scientific knowledge of these activities be used to underpin the design and development of these training aids?

1.4 Research objectives

Objective 1

To establish how the design of a training aid differs from that of a standard product.

Objective 2

To determine the fundamental requirements of a gymnastics training aid.

Objective 3

To establish what criteria may be used to identify a gymnastics skill for which a training aid may be designed.

Objective 4

To determine the biomechanics of the selected skill, and to establish what other considerations must be taken into account in order for a suitable training aid to be designed.

Objective 5

To determine the functional requirements of the gymnastics training aid for the selected skill, and whether the designed training aid incorporates these elements.

Objective 6

To design, build, and evaluate a prototype training aid to help in the learning of the selected skill.

1.5 Scope of research

In order to answer the broad research question posed, it will be necessary to first restrict the study to specific gymnastics skills. This will enable the objectives to be fulfilled, and the information gained from this to be applied to the wider area of generic skill acquisition. This study will detail the biomechanical analysis of two contrasting gymnastics skills in order to gain an understanding of the general application of gymnastics training aids in the process of learning and skill progression.

1.6 Organisation of chapters**Chapter 2: Literature review:**

This chapter is a general review of gymnastics, and previous studies involving gymnastics skills. It also includes design techniques and methodology, discusses previous work and identifies specific requirements of gymnastics training aids. The chapter discusses skill development and learning and how this must be integrated into the design of training aids. Design process and design theories, biomechanical data analysis techniques, and reviews of analysis methods will also be discussed within the chapter.

Chapter 3: Selection of training aids

Chapter 3 discusses how the two key gymnastics skills were selected, analyses questionnaire results and International Coach feedback, and studies market analysis and the suitability of the chosen skills. The chapter includes a review of the chosen gymnastics skills, coaching and variations of coach support for the chosen skills. It then reviews existing training aids for the chosen skills with regard to what is required and expected of a training aid, and discusses their advantages and disadvantages. The generic design methodology for designing a training aid is also discussed within the chapter.

Chapter 4: Handstand analysis

Mechanical analysis: This consists of a mechanical analysis of the handstand on rings, and a comparison is made with the characteristics of a handstand on the floor. A mathematical model of a control strategy to balance a handstand on the training aid is also formulated and discussed.

Data collection: The methodology of the data collection procedures, with diagrams and explanation is detailed. Explanations of the equipment used and set-ups of pilot work are discussed and analysed within this chapter.

Data analysis: Analytical consideration of performance parameters including wrist displacements during balance control alongside the details of the procedures are explained within this chapter. Relationships between cable movement and strain are investigated, and calibrations of the load cells are discussed. Muscle EMG data is also collected and discussed.

Chapter 5: Handstand training aid design and manufacture

This chapter comprises details of the design process utilised within the study. It discusses initial design concepts of the training aid, and then continues to show the progression to the final design. Technical specifications and drawings are discussed in this section, the Product Design Specification is detailed, and calculations for components alongside methodology of manufacture are explained. The final section of this chapter deals with establishing the relevant relationships between the performance parameters of the handstand and design of the constraints.

Chapter 6: Handstand training aid analysis

A quantitative scientific comparison between data collected on handstand on rings and on the training aid is analysed and discussed. This chapter then continues with a

critique and analysis of a prototype training aid with respect to the design requirements. Existing training aids are also analysed, and conclusions are drawn on the appropriateness of the various different training aids.

Chapter 7: Back handspring analysis

Mechanical analysis: A mechanical analysis of the back handspring, including takeoff parameters and position of centre of mass, is discussed with respect to centre of mass velocity, flight path, and landing angles.

Data collection: Methodology of data collection, with diagrams and explanations of procedures are described. Details are given of the research undertaken and of the equipment set-up.

Data analysis: Relationships between variables which affect the flight profile are investigated and correlations between anthropometric measurements and various performance parameters that enable a 'generic description of a good back handspring' are established.

Chapter 8: Backward handspring design and manufacture

Chapter 8 details the design process utilised within this section of the study, it details initial design concepts, and describes their evolution and progression into the final design. Technical specifications and drawings, the Product Design Specification, and calculations for the components are detailed. Relationships are also established between performance parameters and design constraints to permit the construction of a training aid suitable for a range of gymnasts.

Chapter 9: Backward handspring training aid analysis

Biomechanical comparisons between the free backward handspring and the backward handspring performed over the designed training aid are made, with respect to parameters such as joint centre velocities and joint angles at key times such as at takeoff and landing. Results from subject and coach feedback and evaluation questionnaires are discussed and a critique and analysis of the final product with respect to the design requirements is detailed. Training diaries of a gymnast using the training aid to learn the backward handspring, and a gymnast using the training aid to correct her backward handspring are detailed and the results are discussed. Conclusions on the prototype training aid are then drawn.

Chapter 10: Conclusion:

This chapter discussed the suitability of the two training aids, what could have been done differently within the investigation, and future work for further development.

2

Literature Review

2.1 Introduction

This chapter will contain details of the relevant reviewed literature. It will cover the topics considered important in the design of gymnastics training aids, and where possible provide information specifically relevant to this study.

2.1.1 Overview of gymnastics research

There have been many research studies into the sport of gymnastics, but practically none into the design of gymnastics equipment or training aids. The majority of the studies have been into skill development through mathematical modelling (e.g. Brewin, Yeadon and Kerwin, 2000, Hiley and Yeadon, 2003a,b and Arampatzis and Brüggemann, 1999, 2001), and anthropometric and performance analysis (e.g. Bale and Goodway, 1987, Classens et al., 1991 and Faria and Faria, 1989). There have been some studies into equipment liability and hazard assessment (Kirchner et al., 1985, Arnold, 1991 and Gibney, 1993), but only limited to either designed training aids (Groom, 1990 and Suchilin et al., 1988) or equipment design or testing (Gros, 1999).

One book has been reviewed which compiles training devices in the Soviet system. The book was compiled for the International Gymnastics Federation (F.I.G) by Yevseyev in 1991. This book lists over 200 training devices of various types although minimal technical details are available, and there is no evidence of scientific design or whether the equipment has ever been produced. Arkaev and Suchilin (2003) contains a brief section on training aids, but again it contains only rough sketches of nine different training devices and a brief description of the equipment applications within the gymnasium.

It would appear that the majority of existing equipment and training aids have no scientific work published on them which leads to the conclusion that very little scientific work has actually been done in this area. Existing training aids have either been produced for demand with no real scientific work to justify the design, or have been designed through experience and with input from coaches as something either they think will be

suitable or have seen in a gymnasium elsewhere. The majority of gymnastics literature is in coaching manuals and magazines.

2.1.2 Overview of training aid research

Readhead (1997) discusses briefly a list of training aids: Tumble track, pommel mushroom and 'bucket', adjustable height rings, paralettes, bars over pitted areas, trampolines and trampettes, overhead harnesses and the rings trolley trainer. The more common of these training aids will now be discussed.

Pneumatics

Compressed air can be used to provide variable spring properties when designing training equipment which requires adjustable elasticity. Suchilin et al. (1988) comment that the required characteristics of training apparatus is that it should be adjustable for a wide range of conditions and provide quick and accurate adjustment for a given athlete. It is suggested that pneumatic training equipment, such as the pneumatic vaulting horse and pneumatic tumble track described in Suchilin et al. (1988), will allow the athlete-support interaction to be optimal, and will also allow an increase in the volume and intensity of the jumping load without overloading the motor support apparatus of the athlete. In work carried out by in Suchilin et al. (1988), it was found that the pneumatic training equipment allowed more complete realisation of the athlete's speed-strength abilities. Pneumatic training equipment may also be used to develop specific conditioning levels for gymnasts of different classifications, or to improve poor technique.

Belts, Pulleys and Elastics

Devices such as training belts have made major contributions to the safety and injury prevention in gymnastics, and also to learning efficiency by eliminating the gymnast's fear. There are two main types of mechanical belt systems: (1) fixed overhead suspension for use with trampoline, horizontal bar, rings, vault, bars, floor exercises and beam; (2) travelling or trolley runway system for use with tumbling, vaulting and floor exercises as detailed in Pond, 1978.

Pulleys, belts and elastic bungee are found to be utilised within a large variety of different training aids. Groom (1990) describes the benefits of using a pulley and belt system with the last two metres of rope being elasticised, and how such a system permits aerial skills to be preformed from standing. The equipment was described as also being

appropriate for supporting double back dismounts, Tkatchevs and various giant circles when positioned over asymmetric bars.

Belts are also often used in the supporting of tumbling exercises. The value of twisting and non-twisting belts is in their variety of use. A harness with elastic ropes can be attached by ball bearing pulley runners to ceiling level tensioned cables, and can be used either for skills usually supported using a static belt, or alternatively can be used for dynamic tumbling, without the necessity for a coach to follow the entire tumble along the track (Groom, 1990). Such a piece of apparatus is extremely versatile and commonly found in gymnastics facilities.

Fast Track, Trampoline, and Trampette

The trampoline tumble track, also called the fast track, is a long, low tumbling surface that features a bed attached by springs to a metal frame. From a first observation, it appears to be a long narrow trampoline, however the fast track has a greater stiffness than the trampoline, permitting fast tumbling skills to be performed on it. The equipment is an excellent training aid as it gives the gymnast increased air time during skill performance, and this in turn provides the gymnast with a better understanding of skills and more time to make corrections. Another important benefit of the fast track is its low impact properties. Training on a fast track, allows many repetitions to be performed without the wear and tear on joints experienced when training on a normal floor surface (Staff, 2000). Similarly, Warren (1980a and 1980b) discusses the benefits of using a trampette or trampoline as a training aid to help learn tumbling skills such as somersaults and backward handsprings.

2.2 Equipment design and engineering

‘Improvements in human performance can be made through the introduction of technology’ (Haake, 2000).

2.2.1 Biomechanical approach to equipment design

Sports biomechanics generally takes the form of describing movement from a performance enhancement or injury reduction perspective. Sport biomechanists believe that an awareness of the mechanics of movement will better equip and prepare athletes to

learn, teachers to teach and coaches to detect and correct flaws in sport performance. With regards to equipment design, biomechanists are primarily involved in design from an optimisation of performance or from an injury prevention perspective (Elliott, 1999). Zatsiorsky and Fortney (1993), discuss how sport biomechanics can no longer be viewed as merely 'the biomechanics of sport techniques' as other directions of applied research are now equally important and common, such as: the biomechanical basis of sports equipment and apparel.

Yeadon and Challis (1994), explain that by obtaining movement data on an individual athlete, it may be possible to identify those elements of technique that are associated with better performances. However this will provide a limited view of the skill performed. By obtaining data on a number of athletes and identifying the characteristics of the better athletes, it may be possible to gain insight into how training should be structured. A theoretical model, such as the backward longswing model on the rings described in Yeadon and Brewin (2003), though typically based on an individual athlete, may also be able to provide a general description of movement by altering differing model performance parameters as in the Yeadon and Brewin study. Such a study can lead to a more complete understanding of the skill and performance criteria.

Kinematical analysis based on computer-processed video records offers large amounts of useful information about the movement in question. The trajectory in individual planes, velocity of the points, or angles of a segment is often calculated through video data analysis (Zahalka, 1996). This information can be used by sports equipment designers to help them understand better the mechanical requirements of the skill. Once the skill is understood in detail, then accurate training equipment can be developed to support the most complex part of the skill, encourage good technique, train specific control strategies, or even physically restrain poor technique

2.2.2 Sports engineering and design

'Man performs better with improved sports materials and equipment design. Innovation and successful designs are stimulated by the ability of designers to gain inspiration and knowledge about products other than those that they are designing. In design, creative ideas for one product often come from a completely unrelated product. The world of the designer of sports equipment is constantly driven by innovation, with innovation being derived from information and creativity. In the case of sports equipment, insights, and therefore creativity, frequently derive from the raw sport or skill itself'

(Dong, 2000). Figure 2.1 below, attempts to visualise the field of equipment design in a coordination system. Let performance, injury prevention and marketing be the x, y, z axes of a coordination system (Gros, 1999).

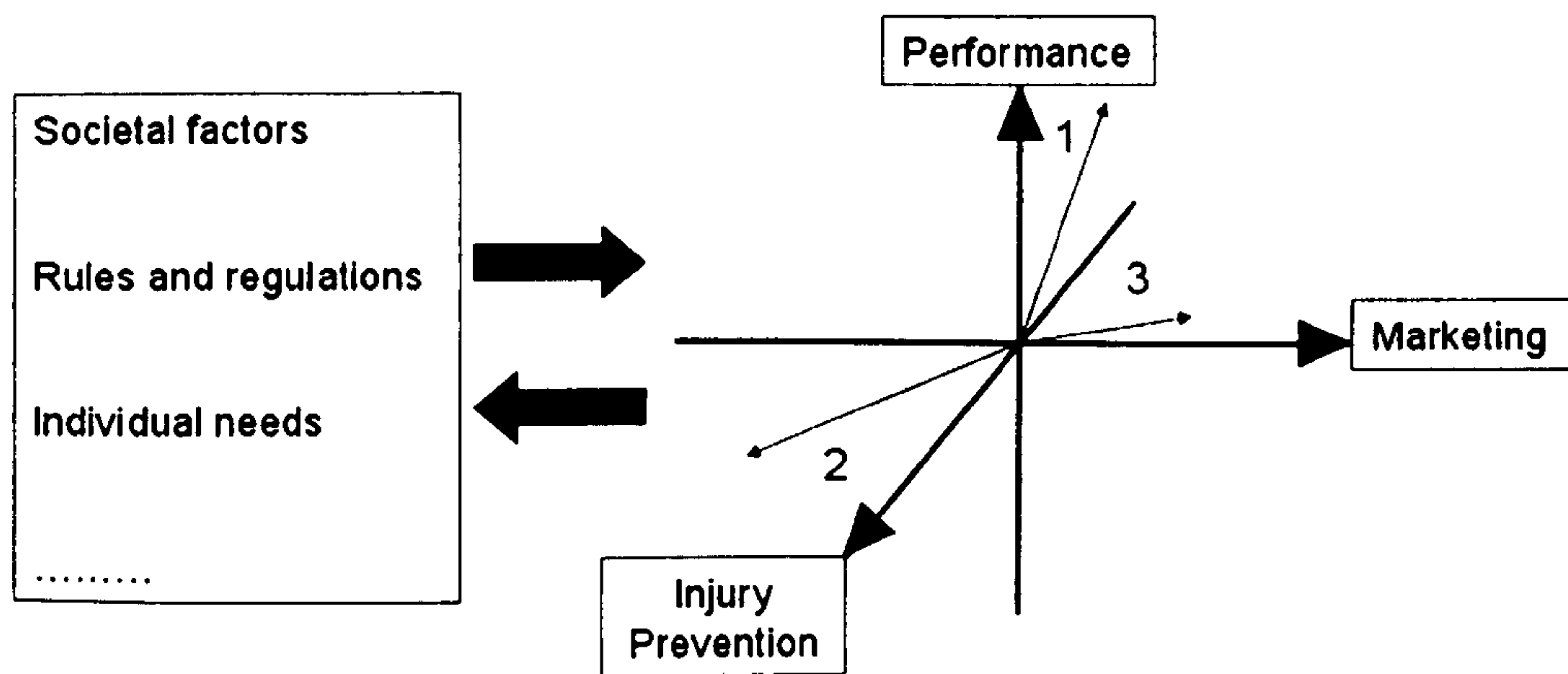


Figure 2-1: Equipment design between the goals of performance, marketing interest and injury prevention (adapted from Gros ,1999).

Vector 1 represents a strictly performance orientated development which accepts the increased risk of injury. Vector 2 depicts the case where injury prevention is improved but the piece of equipment is not likely to succeed since it is not fashionable and detrimental to performance. Vector 3 is the ‘harmless gimmick’

Bolković (1998), claims that the basic aim of designing sports apparatus is to assist and to develop basic motor abilities of athletes. However, sports equipment is not only designed to help athletes improve, but is also involved in the safety aspects of apparatus too, for example Gros (1999) comments that injury prevention safety considerations play an important role in equipment design. Through sports design, new equipment can be created, or existing equipment improved, new techniques evolve and the standard of sport improves. It has been found by Gros (1999) that a key to successful equipment design is the use of feedback acquired from coaches and athletes not only at the beginning of a project, but during the development process as well. Gros comments that not only is the solid science crucial for the design of a suitable piece of sports equipment, but also the practitioners perception of the ‘feel’ of the equipment, and that perfecting this combination is an iterative process. A procedure discussed by Gros in the development of a landing surface for gymnastics was to evaluate subjects and take measurements, and to use a reliable and repeatable testing procedure. From three experimentally established basic-parameters, (the compression, rebound height and the peak force), the thickness of the matting was altered, and this was followed by further testing.

Suchilin et al. (1988) discuss how the use of foam-filled landing areas, tumbling and trampoline tracks, sprung floors and other such equipment in the training of gymnastics has proven to be rather effective. They continue to state that modern training equipment needs to be constructed so as to provide the opportunity for athletes to use their motor abilities as much as possible, first in artificial conditions and then in standard competitive ones, but all as safely as possible. Suchilin et al. (1988) also explained how an important characteristic for the success of a piece of training equipment is that it must be adjustable for a wide range of conditions and be adjustable for a variety of athletes to permit multiple users' and multi functional use. Kreighbaum (1996) explained that equipment must also be comfortable to use, aid in successful performance, be affordable as well as fit the users size, shape, strength and ability.

Training aids such as the 'water rower', which duplicates both the physical exercise of rowing and the attendant sounds of rippling water; the 'compuTrainer' (a computer controlled electro-mechanical bicycle) and the 'flyaway' (an indoor skydiving facility) are examples of training aids designed for sporting activities described by Busch (1998).

2.2.3 Material considerations

The prominent materials used to manufacture gymnastics equipment are wood of various types and rubber/plastic, but mainly metal and foam. Materials used for the design of a piece of equipment must adhere to the relevant British Standards; for gymnastics equipment it is BS 1892-1: Gymnasium equipment - Specifications for general requirements. The standard mainly specifies the grade of material to be used and which British Standard it must comply to; for example for wood it specifies the permissible types. There is however no mention of foam but there are separate standards for matting properties which will be discussed in Section 2.2.7.

Mills (2000), comments that foam must be protected against abrasive damage, and that this should be done using flexible bonded covers. He also mentions that as foams are a fire risk, the products must usually pass fire tests; consequently fire-retardant additives can be added to the foam polymer. The bonded cover also assists by slowing the ingress of air to the foam. Properties such as fire resistance and friction/abrasion are the types of criteria covered by the British Standards for matting. The other property of matting which the British standard requires is compression, measured through impact testing, this will be discussed in further detail in Section 2.2.7. With regards to the material property considerations of foam, maximum depression values are crucial, as are the materials

compressive characteristics. Kuncir et al. (1990), reported that the maximum depression of polyethylene foams was measured to be approximately 75%, and that this value would affect the compressibility of the material used. It will be important to establish such values for any foam materials used to ensure that the end product will be capable of passing British Standards, in particular the impact testing.

2.2.4 Safety considerations

‘Safety and the prevention of injuries are important considerations in gymnastics’ (Mitchell, 2002). ‘In order to prevent accident situations objects used have to be designed and translated into reality in such a manner that no hazard may appear’ (Kirchner et al., 1985).

Product Liability

Negligence and product liability are important areas for all equipment manufacturers to be aware of. All manufacturers have a duty to do all that is prudent and reasonable to prevent the release of a defective product into the market. Products can be defective due to problems with the design, manufacture or marketing of the product. In general it is the manufacturers’ duty to try and provide a defect-free product. This includes at least, the duty to: avoid design defects; inspect the product before shipping; ship it in a way calculated to protect it from becoming defective as a result of the shipping; warn the potential user of the foreseeable risks of injury involved if the product is used incorrectly; market the product in a way that alerts the potential users to techniques for its appropriate and safe use (Arnold, 1991).

A manufacturer must adhere to the standard of reasonable care in the manufacturing and design of the sports equipment, so that it is reasonably safe when used for its intended purpose and in the manner intended. A manufacturer’s warning will be inadequate if it does not specify the risk presented by the equipment, if it is inconsistent with how the product would be used, if it does not provide the reason for the warning, or if the warning does not reach foreseeable users (Gibney, 1993). Adequate and appropriate instructions of safe technique should be shipped along with the product. Failure to warn and instruct is a marketing defect and the manufacturer has a legal duty to market the product in such a way that alerts any potential user of the techniques for the product appropriate and safe use.

The theory of strict liability can be used against a manufacturer who sells a product, which was defective and therefore unreasonably dangerous when it left the factory. The injured plaintiff does not even have to establish that the manufacturer was at fault in any special way. In most jurisdictions the plaintiff only needs to show three required elements: the product contained a defect which was unreasonably dangerous to person or property; the defect existed at the time of the sale of that product by the manufacturer; the defect caused the injury (Arnold, 1991).

Breach of warranty provides another reason for recovery in a product liability suit. When a manufacturer warrants (guarantees) that a product will meet certain performance criteria and the product fails to meet these criteria, the manufacturer may be held liable for breach of its express contract. Implied warranties of merchantability and fitness for a particular purpose are also of some but rather limited usefulness in sports settings (Arnold, 1991). Such implication must be seriously considered during the manufacture and testing of any new piece of training equipment, and relevant documentation should always be produced before any human testing takes place.

Specifications, Maintenance and Life Expectancy

Gymnastics equipment manufactured by reputable companies is designed to meet FIG (Fédération Internationale de Gymnastique) specifications and tolerances. The specifications and designs take into account the dynamic movements the equipment will be subjected to during performances by the gymnast (Cysewki, 1989). There are several British Standards governing manufacturing and design of gymnastics equipment, and they will be discussed fully later in Section 2.2.7.

As expected, companies take this responsibility of safety very seriously, Spieth Anderson (2002) advise that before using equipment the coach should always inspect for proper stability, loose fittings and loose or damaged parts. They also comment that it is essential to replace any worn, defective or missing parts before using the equipment and that equipment maintenance must involve: making sure that all nuts and bolts are fastened securely; replacing all warning or instruction labels that have been damaged or removed; checking all floor mountings to make sure they are securely attached to the mounting surface; and checking cables, cable terminators, cable hardware and pivot points. Items such as cables should also be examined for wear, loosening and alignment, and replaced immediately if worn or damaged. The general warranty on gymnastics equipment is a standard one-year guarantee. 'United Athletic International Warrants to the consumer that the products herein sold, except those products manufactured according to the design,

prints or specification of the consumer, are free of defects in material and workmanship. This warranty, together with any and all warranties implied by law, shall be limited to a duration of one (1) year from the date of purchase by the original retail purchaser' (United Athletic International). It is also recommended that many other items or equipment components such as certain bar fittings are changed every three years, which suggests a life expectancy of no longer than this duration. Spieth Anderson (2002) explain that based on data supplied by the FIG safety symposium, they strongly recommend that horizontal bar rails be replaced every three years to reduce the possibility of bar breakage. If this replacement is due to the wear and fatigue of such a piece of equipment, then time constraints such as these must be considered during the design of gymnastics equipment, to ensure that the equipment designed will not fail due to fatigue before a standard three year period. It will however also be necessary to perform other calculations and testing to ensure that components used in the design of gymnastics equipment are suitable for purpose. This will ensure that no component should fail under standard loading, hence reduce the chances of injury inflicted by equipment failure.

2.2.5 Design methodology

A study by Fairlie-Clarke and Clarke (1993) identified and examined the required elements of a methodology to produce a framework for product design that was specific to a particular company. The process used in this study if generalised can be adapted and re-specialised for any product design. The study identified elements required for a framework for product design: the formulation of a product strategy and the methods used to influence and control the decision process in product design; the structure of the company; all tasks associated with product design; documentation to support all aspects of the product; the flow of data that define the product; the flow of information that is required for product design; mechanisms used to influence and control the output of the tasks; means used to perform the tasks; the review and formal decision mechanisms.

Elements for a methodology were also established: a system model to represent at a generic level of abstraction the necessary and sufficient elements of the design process; the framework must relate to the strategic objectives of the company; methods to be used to establish the companies product design systems and procedures; the generic model can then be used as the basis for a more detailed model of the product design system; finally a higher level model to represent outcomes of the main functional activities, reporting and documentation requirements, and the evaluation and decision process.

2.2.6 Design processes

Theobald et al. (1993) tells us how the translation of a design concept into a scheme presents the designer with a number of tasks that require significant amounts of time and effort. Amongst these tasks are component and material selection, form, size optimisation and spatial configuration. The various stages that a product goes through during its design is frequently depicted as a linear sequence of events (Wright, 1998). The diagrammatic model of the various stages of the design process, represented in Figure 2.2 (broadly attributed to French, 1971) describes the initial part of the process as being the determination of the customer requirements.

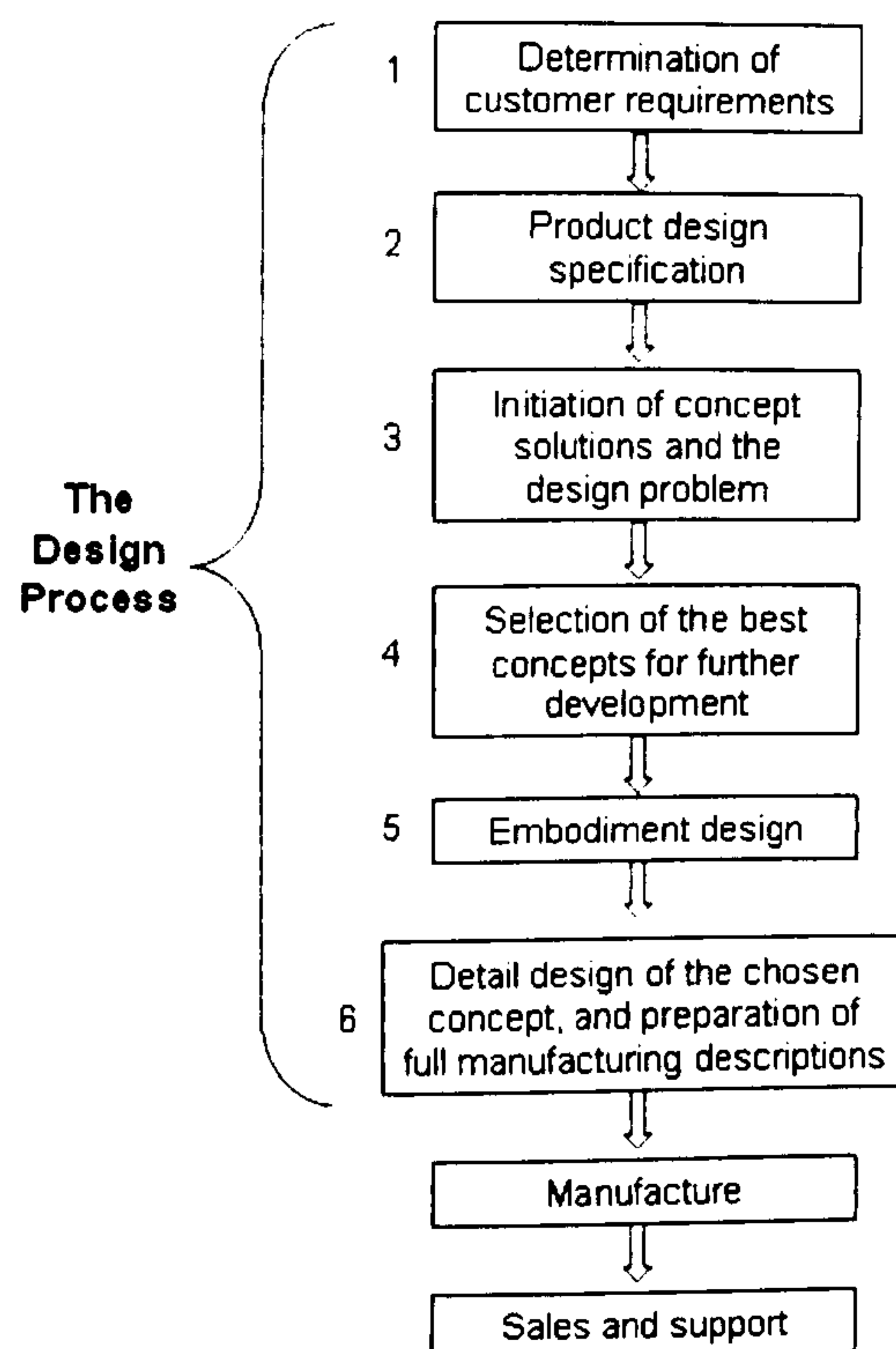


Figure 2-2: The design process as a linear activity (adapted from Wright, 1998).

Quality function deployment (QFD) is a means by which customer needs can be identified and transformed into technical requirement and prioritised for the Product design specification (PDS), and competitor analysis can be performed. Norell (1993) explained that an important tool in the QFD is the planning matrix, '*the house of quality*', where the main activity is to separate customer needs from technical solutions. The PDS lays down the customer requirements in a comprehensive and as complete a manner as possible.

Next in the chain is the creative stage. There are three routes to creativity: the development of insight, the abstract-concrete-abstract cycle, and design principals (French, Chaplin and Langdon, 1993). Creativity is crucial within the design process, and it can be

introduced in many ways. The most common technique of initiating creativity is Brain Storming, which involves a conscious effort to provide a conducive environment for creative thought. During this process, both suspended judgement and multiple concept generation will be utilised. The Mind-mapping technique is also commonly used, and this technique attempts to provide a means of rapidly externalising the ideas generated in the brain (Wright, 1998). It is necessary to use methods such as brainstorming along with mind-maps and other innovation tools during the design and development of training aids to ensure that the best concept is found.

If there are multiple possible solutions to the design question, there can be problems in presenting these options to allow further development to take place. A morphology chart is a matrix of functional requirements verses possible solutions; it is generally a graphical representation, and this can be used to organise the different options. The designer can work down the matrix deciding upon which solution to use for each functional requirement, and how these various ideas may fit together into a complete system (Wright, 1998). To be able to compare concepts, it is necessary to include information from all the functions within the organisation: for example biomechanics, engineering, and sports coaching. A schematic explaining the relationship between the evaluation matrix, PDS and requirement tree can be seen below in Figure 2.3.

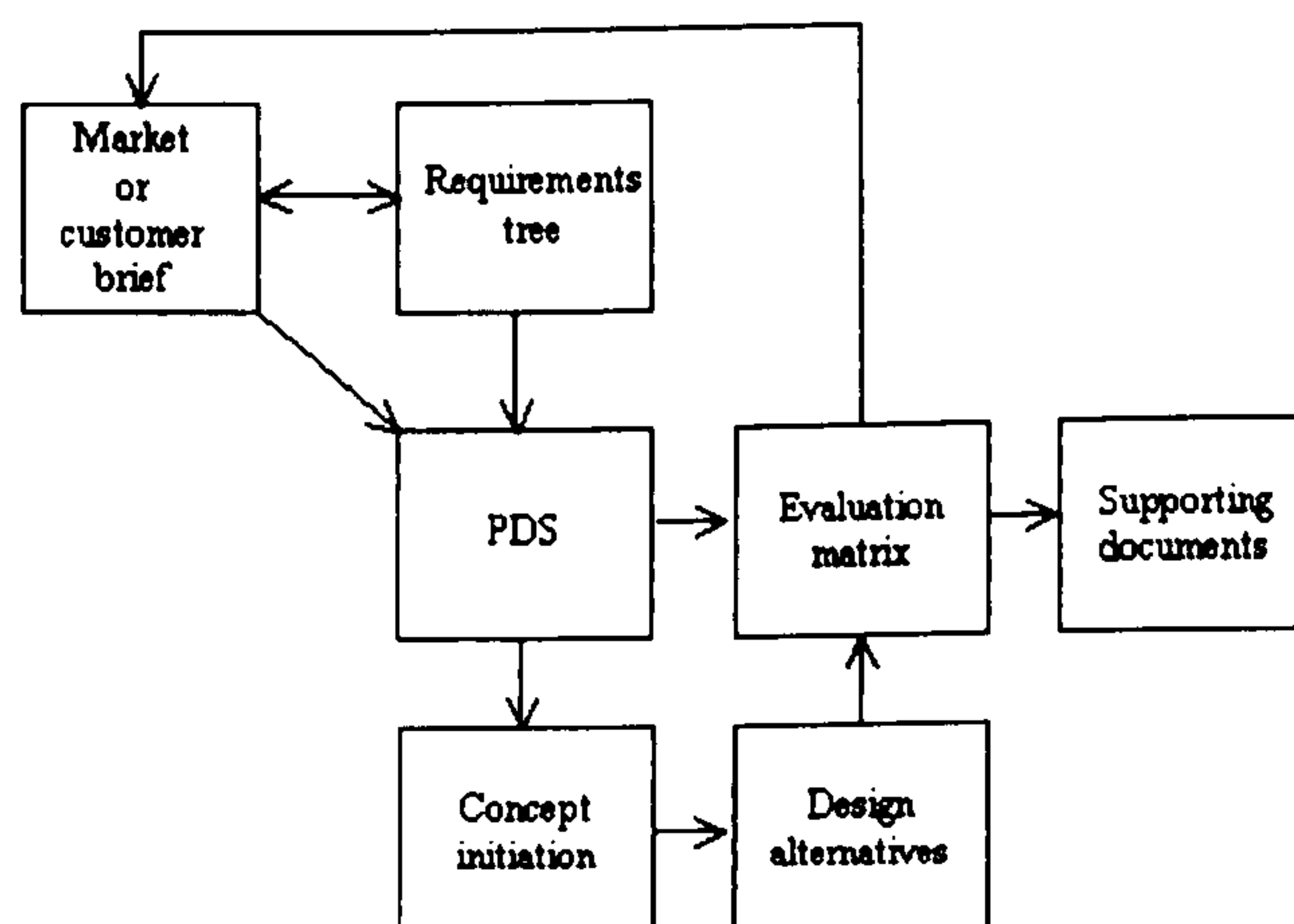


Figure 2-3: The relationship of the components of the product design process (adapted from Wright, 1998).

During concept analysis, in addition to the testing of the company's own concepts, the development function will frequently be concerned with the testing of competitor products. This can provide a 'benchmark' against which the company's product can be evaluated, where the ability to evaluate alternative design options is crucial to the final outcome of the design process. The needs of the customer can be defined in terms of

objectives and constraints, an objective being considered as a requirement written in unquantified terms, while a constraint is considered to be a requirement written in quantified terms. A requirement tree can provide a means of 'thought ordering' for an individual designer working alone. It also provides a means of communicating thoughts on objectives and constraints to other designers.

The success of a new product is a realistic concern to all design engineers, and to increase the chances of success for a new product it is always advisable to first evaluate the market. A market can be segmented on the basis of any variable or group of variables that proves to be useful in identifying market opportunities. It is important that these segments be considered when designing a product, as the wider the variation of segments a product covers, the more likely sales will be achieved. Having identified the segment of the market in regard to their product, companies have to make strategic decisions about targeting. These decisions will determine whether the company directs their product to a single segment, several segments or to the entire market. When a company is in the process of developing a new product, or modifying an existing one, it needs access to all of the information available to the purchaser in terms of competitive choices, to permit a high chance of success in entering the market (Wright, 1998).

With any new product there is associated risk, and from a product designer's point of view it is convenient to identify two types of risk: market risk and technological risk. Market risk is concerned with the possibilities that: the market requirements have not been correctly defined in the first place; the market requirements have been correctly determined but they have not been correctly or adequately recorded in the product design specification; the market requirements were correctly specified originally, but have changed during the time taken to prepare the product for launch. Technological risk is concerned with the possibilities that: an adequate technical solution cannot be identified for one or more of the product's sub-systems; an identified technical solution turns out to be inadequate on function, cost, time for development, or other grounds; a supplier of a key sub-system or component fails to provide a suitable solution (Wright, 1998). The assessment of technological difficulty must include an appraisal of all aspects of the system under consideration.

2.2.7 British Standards

There are several British Standards governing manufacturing and design of gymnastics equipment. They mainly detail specifications for materials, matting and

landing areas, with regards to material properties and thickness (BS EN 12503-1:2001). Part 4 of this standard has details for determining the shock absorption properties of the mat, parts 5 and 6 detail the procedure and requirements for determining the base and top friction of the matting, and part 7 details the procedure to determine the static stiffness of the matting. BS 1892-2.10:1990 and BS 1892-3:2003 contain the specifications for fire safety requirements for mats, mattresses and landing areas. There are two British Standards for general gymnasium equipment, BS 1892-1: Specification for general requirements, and BS EN 913:1996: Gymnastics Equipment – General safety requirements and test methods. These contain the required hazard assessments such as stability, strength and impact tests, general safety requirements such as surface finish, shearing, trapping and crushing points. The standard also provides full details on the test procedure required for the equipment to pass the British Standard requirements. It is important that all relevant standards must be adhered to when designing and manufacturing any piece of gymnastics equipment

2.3 Experimental and theoretical research

‘Sport biomechanics should be a balanced mix of experimental data and theoretical modelling if a realistic understanding is to be achieved’. ‘While the coach will use a subjective qualitative analysis of sporting movement in order to determine what advice to give, the researcher in sports biomechanics must make use of objective quantitative data (Watkins, 1987a, b)’ (Yeadon and Challis, 1994).

The techniques currently used to measure motion include photographic and video recording devices, specialised transducers such as goniometers, force plates, accelerometers and strain gauges. There are also on-line movement analysers, which are multi-channel instruments that continuously measure and automatically calculate angular and three-dimensional coordinate data (Atha, 1984).

2.3.1 Experiment design

Yeadon and Challis (1994) discuss that the initial testing of theoretical predications may be accomplished using available observational data, while the subsequent testing of refined theories may require carefully designed experiments (Figure 2.4).

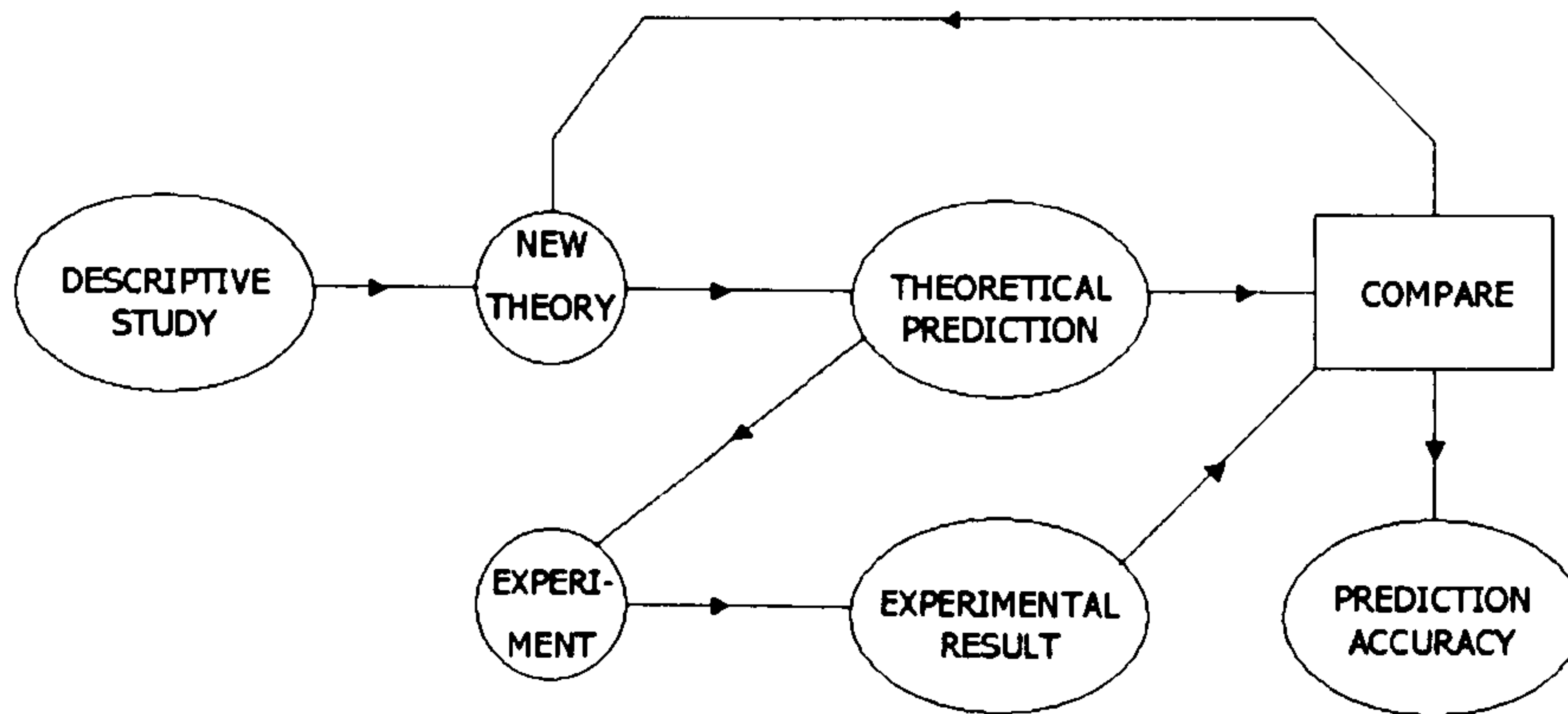


Figure 2-4: The theory-experiment cycle of scientific method (adapted from Yeadon and Challis, 1994).

There are several different types of data available for collection during investigative work. The ones most prevalent for the particular study must be considered.

Automated Systems and Movement Measurements

Gros and Terauds (1981) explain that highly sophisticated data acquisition and analysis instruments in conjunction with careful adherence to biomechanics cinematography procedures allows the researcher to gather comprehensive, relevant and reliable data through a non-invasive technique in competitive environments. The labour-intensive and time-consuming nature of manual digitisation has led to the development of automatic systems which have greatly reduced the time required for motion analysis, but has also led to the necessity of the attachment of markers to the subject's body segments. There are different categories of commercial instrumentation commonly used to measure whole body motion. 'Using film and applying reference markers to subjects during activities, gives a kinetic analysis of the motion. Using different types of transducer on the subject, or as an interface with the subject makes it possible to also perform a motion analysis of the activity' (Ekström and Karlsson, 1985).

The first category utilises equipment that provides a visual record of body segment positions, while the second category utilises magnetic sensors to determine the position and orientation of the body segments (Richards, 1999). The most common type of automated system is a video-based system. A popular example of this system is the Vicon motion system which is an automated marker tracking system. This utilises markers covered in retro-reflective tape in conjunction with camera ring lighting, which is often stroboscopic using infrared LEDs. The advantages of these passive markers are that no wires or batteries are needed, and they are inexpensive to replace. Markers on anatomical human landmarks are often used to measure the movement of the whole limb segment or bones when studying human movement. The disadvantages of such systems are the

interference caused by sunlight and the difficulty in automatically identifying markers, especially when two body segments move across each other obstructing the view of the camera system. 'It has been shown that relative movement of two such markers, due to the movement of soft tissue, is by far the greatest source of "noise" in the measurement. This noise is not random, white or zero-mean, and it is closely correlated with the movement being studied' (Macleod and Morris, 1987). A third type of system (CODA), as described in Yeadon and Challis (1994), is based on scanning mirrors and coloured retro-reflective prismatic markers. This system works by using rotating mirrors which sweep fans of white light through the movement space so that coloured light is reflected back by each prism.

The aforementioned systems have the advantage that the data is available much quicker than with manual digitisation. It must be remembered, however, that automatic systems can only give the locations of the surface placed markers, algorithms must be used to relate the marker position to the joint location for the extraction of joint movement. The operator of a manual digitising system however can estimate joint centre locations, although not always accurately.

A further system is a vision-based/marker-free tracking system. These systems are considered to be a more flexible means of human motion capture than commercially available system such as opto-electronic or laser-based systems. Yeadon et al. (2004), explain that tracking the kinematics of human motion is a complex problem without the assistance of artificial markers as used in the Vicon system. The nature of the movements and the regular occurrence of occlusions of one body segment by another are just a few of the complications of these systems. Several variations of such systems have been developed: the 'log-tracker', a system developed for tracking the motion of different parts of the human body (Long and Yang, 1991), this system has successfully tracked moves such as a cartwheel, and flairs on pommel horse; a visualization system called "Multi-motion" has been developed by Yagi et al. (1998), which displays the images from jump to finish, overlaying them like a scene from a stroboscopic camera; the model-based automatic tracking system which was successfully used to track aerial gymnastic movements from a trampette (Yeadon et al., 2004).

When gymnasts are fitted with retro-reflective markers, they should be positioned over the joint centres on the side of the body closest to the cameras. Data is then collected using cameras operating around 50-100Hz. The markers need to be light and small so as not to interfere with the movement of the gymnast. However, the markers must not be so small as to interfere with the digitising or automatic motion analysis of the skill performed. This is an important factor to be considered during a collection data on dynamic skills. It

is expected that in various positions throughout gymnastic skills there will be occasions when some markers will be obscured from view. If this creates problems for an automatic tracking system, then manual digitisation may have to be an alternative.

Angle Measurements

To be able to accurately compare the technique of a performance, joint angles may need to be measured. This can be achieved using mathematical programs for which the input is the joint centre positions and some automated systems will output joint angles if provided with the code to run such a function.

An alternative way of measuring joint angles is to use goniometers, which range from simple two-dimensional goniometers to the more complex tri-axial goniometers (Yeadon and Challis, 1994). However with the types of movement involved in gymnastics, additional pieces of equipment being attached to any gymnasts being tested will hinder their natural movement, and this may produce errors in the movement data collected.

Acceleration and Force Measurements

Acceleration in sport biomechanics is generally measured with accelerometers. An accelerometer is an electromechanical device that will measure acceleration forces. The most common type of accelerometers use the piezoelectric effect. These contain microscopic crystal structures that get stressed by accelerative forces, the forces causes a voltage to be generated by the crystal structure which is converted into acceleration using a known linear scale specific to each accelerometer. There are however problems associated with mounting the accelerometers onto the human body. With skin-mounted accelerometers, there can be significant noise added to the signal due to skin soft tissue movement. It is possible to use cortical pins, but this is an invasive procedure, and so very rarely used. Accelerometry can be used to determine the moment of inertia of body segments, and also to determine segmental accelerations (Peeraer et al., 1987).

Force measurements can be obtained using either accelerometers or force platforms, however in these situations mass must also be taken into consideration, and it may sometimes be necessary to manually zero the equipment in order to collect the data required. When performing force analysis in gymnastics, it is necessary for the gymnast to perform the skill in a safe environment, and for the condition to be as normal as possible. In a study on tumbling by Koh et al. (1992), ground reaction forces measured with a force plate beneath the left hand during each skill performed were sampled at 100hz. There can

be complications of repeatability with hands or feet hitting the force plate at the same location every time, but with synchronised video data, extreme differences in results can be investigated by looking at the video data and comparing locations of limb positions or differences in technique.

In the work done by Unold et al. (1974), force measurements were taken in Artistic Gymnastics, to observe what forces influence the human body. For all the measurements taken, three accelerometers were attached to the subject, one at the shinbone, one at the hip and one on the head. All of the locations were bony surfaces to eliminate skin movement error. The measurements obtained were of the accelerations present with different landing types on different surfaces.

Strain gauges can also be utilised in order to establish force relationships. In a study on the rings longswing by Yeadon and Brewin (2003), strain gauges were placed in series with the rings cables in order to measure the tension in the cable during the performances.

Muscle Measurements

Electromyography (EMG) is the study of muscle function through analysis of the electrical signals emanated during muscular functions. DeLuca (1993) explained that EMG provides easy access to physiological processes that cause the muscle to generate force, produce movement and accomplish countless functions. EMG has widely spread use such as medical research, rehabilitation, ergonomics and sports science (Konrad, 2005)

2.3.2 Error

Error occurs in modelling and data collection. In modelling, the main errors involved are through incorrect assumptions or simplifications. In a paper by Yeadon (1990) it has been shown that anthropometric measurement error, from which segmental inertia parameters are calculated have a small effect on a calculations, whereas video digitisation errors can account for much more substantial errors. After the calibration of the measuring device, some unbiased assessment of accuracy of the measurement system should be performed. In an ideal experiment, the conditions should differ only in the independent variable, and so experiments should be designed to eliminate systematic differences.

The sampled signal from video of the paths of human body landmarks, are composed from two components: the underlying true signal, and the noise that can infringe

on the true signal. The error is generally present in two forms: systematic and random. If the sources of systematic error can be identified they can often be reduced by subtracting them from the raw data. For the rings, the effects of the swing observed could be reduced by filtering at the same frequency as the swing, hence leaving only the required data. Random noise, however, cannot be directly identified, but frequency analysis of human movement indicates that random noise is predominantly of a higher frequency than the movement signal being analysed.

2.3.3 Anthropometric data

Cagan, and Vogel (2002) describe the use of anthropometric analysis in product development as being complemented with a detailed understanding of biomechanics. Generalised gymnastic anthropometric data detailed in Caldarone et. al (1986), Claessens et al., (1990), Bale and Goodway (1987), and Faria and Faria (1989), can be used to provide first approximation dimensions of the design of gymnastics training aids. Anthropometric data can also be used to establish inertia parameters of human movement. Yeadon (1990) developed a model which permits the determination of personalised inertia parameter values from specially designed anthropometric measurements. The human body is modelled using only 40 geometric solids which are specified by 95 anthropometric measurements. Previously, experimental techniques such as by Hay (1973), Hatze (1975), and in Tichonov (1976) have been proven less suitable for gymnastics investigations as they are not capable of determining the moment of inertia of central segments such as the pelvis, or of determining the moment of inertia of a limb about its longitudinal axis, both of which are highly required in order to model a gymnastics skill accurately.

Another mathematical model developed by Hatze (1980) is made from seventeen rather complex segments which require 242 anthropometric measurements, and combines the pelvis with the bottom half of the torso. The Yeadon model however has five separate solids for the chest-head, one for the thorax and two for the pelvis. This model has been used for many gymnastics studies, including two rings studies, one by Brewin, Yeadon and Kerwin (2000), and one by Yeadon and Brewin (2003), and a high bar study by Hiley and Yeadon (2003a,b). From the work reviewed, it has been concluded that any anthropometric data collected in the study will be in accordance with the model of Yeadon (1990) due to the suitability of the model for gymnastics study, and due to the simplicity of the measurements required to use the model.

2.3.4 Ethical Clearance

It is necessary to seek ethical clearance before collecting data on humans, especially children. Specific clearance will be required as this study will necessitate humans testing a new piece of apparatus. Loughborough University Ethical Advisory Committee recommend that for young people under 18 years, investigators should not normally contact them or their parents directly. Wherever possible, contact should be made via a third party (e.g. gymnastics coach). Investigators should also ensure that both children/young people and their parents/guardians are fully briefed as to what is involved in the research, including details of how and when data collected during the study will be used. All instructions should be clear and easy to understand, especially for the younger participants, and they should fully understand that both the opportunity to ask questions, and a continual opportunity to withdraw at any time is provided.

It is also advised that guidance be taken from the Criminal Records Bureau (CRB), that investigators should be cleared by the CRB, and that they should be the same gender as the children participating. If both boys and girls are present at the data collection, then investigators of both genders must be present but only one needs to be CRB cleared, and coaches where possible should be present at all times.

2.4 Learning, growing, and motor control

All human skill involves the coordination of perception and action. However, different types of skill place varying emphases on the contributions required by perceptual processes, cognitive decisions, and motor control (Holding, 1989).

2.4.1 Skill acquisition

Human beings are capable of highly skilled activities, which often involve complex interactions between sensory and motor processes. Visual information has been shown to play an important part in the timing of motor acts, and feedback has been shown to contribute to both the control and acquisition of human skills. Holding (1989) explained how in early learning, before any appreciable skill has been acquired, the need for corrective feedback is undoubtedly great. In most tasks in the early stages of skill learning, humans tend to rely heavily upon visual feedback, with kinaesthetic cues from joints, tendons, and muscles assuming greater importance as skill develops to the point where the

learner can perform it blindfolded. 'Aside from practice itself, information feedback provided to the performer about goal achievement is considered to be one of the most critical variables affecting skill acquisition (Bilodeau, 1966; Newell, 1976; Schmidt, 1988)' (Winstein and Schmidt, 1989).

Holding (1989) also discuss that any precise, adjustive movement may be regulated by feedback in two different ways. In the form of terminal knowledge of results, occurring at the end of a movement, the feedback information is used to guide the formulation of the next response; it thus tends to be retained and to have a durable effect on skill learning. The other way in which feedback functions, has less effect on learning. In its more immediate form, known as concurrent feedback, the information guides the course of ongoing movements, for example maintaining balance, provided that these are controlled actions rather than merely ballistic. This type of feedback has been suggested to provide a lesser affect in the learning process by Holding (1989), as it is not retained in the same manner as feedback received at the end of a performance.

In gymnastics, feedback would also be provided in the form of verbal instructions from the coach, as like terminal knowledge, this would generally be provided at the end of the performance. If the gymnast were to use a training aid on their own, as no verbal feedback could be directed, the required information would have to be received in a different format. This could be through contact with the equipment if the skill was performed incorrectly, through sensors, for example motion sensors connected to lights or buzzers, or through the training equipment reacting in a certain manner to an inaccurate technique.

There are two classifications of skill. 'Open' skills, require a good deal of interaction with external stimuli, whereas a 'closed' skill can be performed without reference to the environment. Open, perceptual, skilful controlled movement can be either simple or complex, as can closed motor habitual automatic skills (Figure 2.5). These differences in complexity, in practice, often run parallel to the difference between gross and fine skills, although the correspondence is far from perfect. Gross skills are those which involve whole-body movement, and, barring competition gymnastics, are often less complex than fine skills which require manual dexterity.

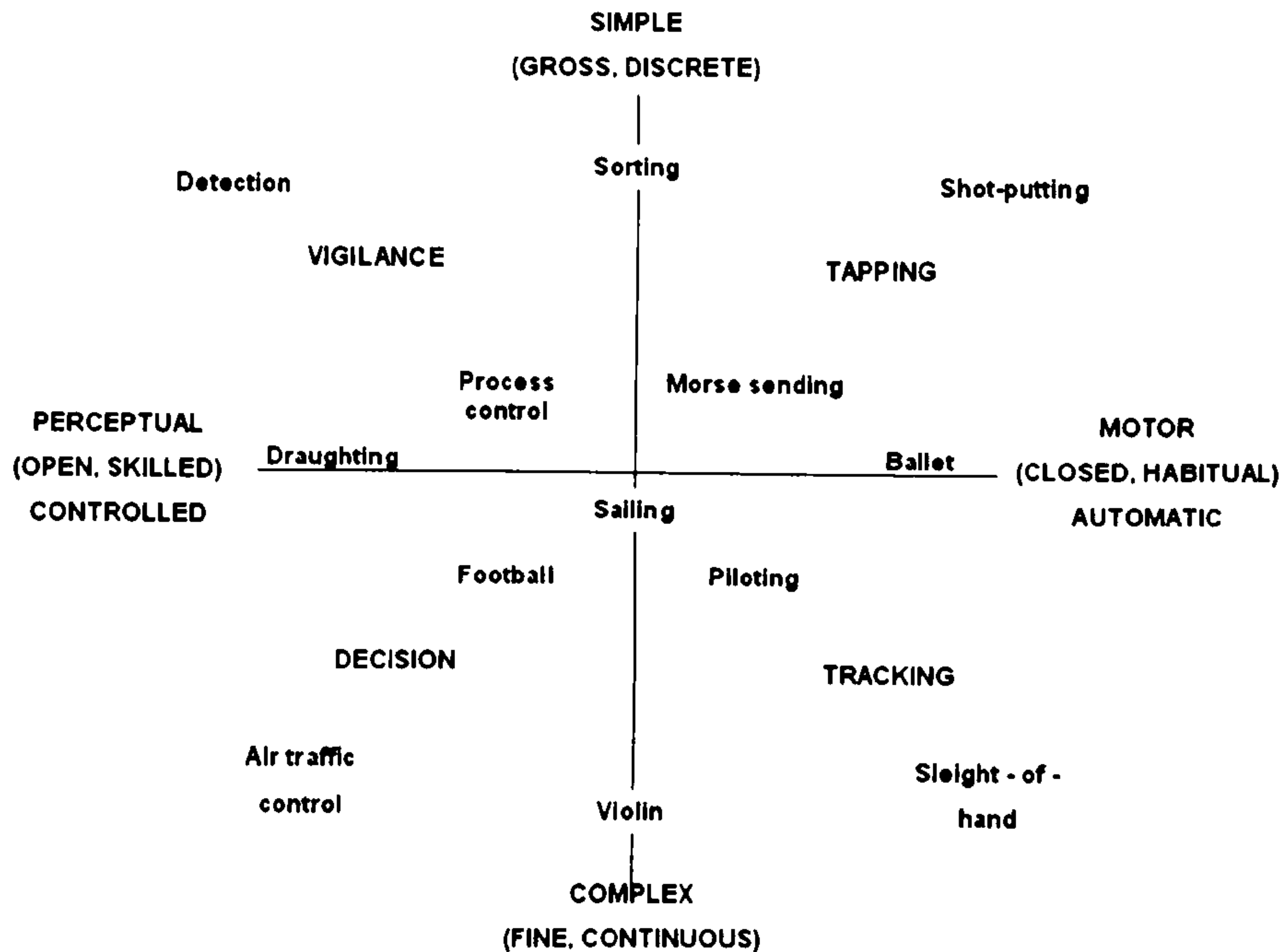


Figure 2-5: A suggested classification of skilled tasks (adapted from Holding, 1989).

Holding (1989) explained that the terminology is unfortunate since 'closed' skills are virtually 'open-loop' in feedback terms, and vice versa. A closed-loop system emphasizes the role of sensory feedback in movement, while an open-loop control during which movement becomes stored in memory and can be executed without constant reference to feedback. In fact, we may compare the 'open-closed' distinction in turn with the older distinction between skill and habit, since it is only the closed skill, which readily becomes habitual and stored in the memory. When learning skills, once the technique has become a habit it is very hard to alter, therefore it is important that the habits learnt by the gymnast are technically correct.

If the relation between stimuli and response remains the same then learning can proceed until performance becomes habitual. This is the requirement of any piece of training equipment. A method often suggested to convey a 'feeling' for movement during the early phase of skill learning is physical guidance, and this is nearly always the technique used in gymnastics (Summers, 1989; Salmoni, 1989; Wickens, 1989).

2.4.2 Reaction time and anticipation

If a person always waited until the appropriate or expected display cue occurred before initiating a response program, the actions would always be mistimed or late. The delay time comes about because a fixed reaction time must elapse between stimulus and response. 'A reaction time considering all possible system-delay intervals will total

something approaching 200 milliseconds for a simple reaction time following a warning signal. Reaction time to a probable stimulus is much faster than the reaction time to an improbable one' (Holding, 1989).

It can be shown that individual skill development accompanies an increasing capacity for anticipation, for example, sway in handstand is expected, and so can be controlled, but landing in the wrong position during a complicated vault is often unexpected and the gymnast may collapse before having a chance to react. It is this important concept that introduces the requirement for efficient training aids to be developed.

2.4.3 Human growth

If a training aid is to be designed to be suitable for a range of gymnasts, it is necessary to understand the patterns of growth of a young child. Krogman (1972) provided information showing that from birth to approximately fourteen years of age, both girls and boys had similar growth rates. It also showed that both genders from the age of seven to thirteen had similar independent growth rates of the leg, trunk and combined head and neck, and that these trends were approximately linear.

Krogman also detailed that both boys and girls from the age of two to sixteen had approximately the same linear growth of both shoulder width and sitting height, with the average shoulder width being approximately 35cm at the age of fourteen years. The pattern of physical growth is grouped into five stages by Krogman (1972): early childhood (3-6 years); middle childhood (6-9 years); late childhood (9-11 years); early adolescence (girls 10-12 years, boys 11-14 years); late adolescence (girls 12-16 years, boys 14-18 years). Sinclair (1985) provides us with information about the relative sizes of body parts (Table 2.1). This may become relevant if when designing a training aid, the length of gymnast body segments is important to design dimensions or to dimension relationships.

Table 2-1: Lengths of body segments as a percentage of standing height (Sinclair, 1985)

Age	Head and neck	Trunk	Upper limbs	Lower limbs
Birth	30%	45%	10%	15%
2 years	20%	50%	10%	20%
6 years	15%	50%	10%	25%
Adult	10%	50%	10%	30%

2.5 Chapter summary

From the literature reviewed, it has become apparent that it is important to perform a biomechanical analysis of the required gymnastics skill in order to obtain a full understanding of the involvement of the movement. Analysis of multiple athletes where possible will also provide a more generalised view of these requirements.

It has been established that video can be used to provide movement data and information on the velocities of points on the body or joint angles (Zahálka, 1996), but also that the experiments must be repeatable and reliable (Gross, 1999). Other data collection techniques have also been discussed, and the types of data which are possible to collect are: displacement and joint angle data, acceleration data, force data and EMG muscle data. It has however been expressed that the data which will need to be collected must be identified through an initial analysis of the chosen gymnastics skill. This will be discussed in greater detail in Chapter 3. If anthropometric data is required for the data collection, from the literature the Yeadon (1990) model has been shown to be most relevant to gymnastics studies.

The literature has highlighted that it will be important to obtain coach and gymnast feedback at the beginning and throughout the project (Gross, 1999), to ensure that customer requirements are assessed. General design processes such as PDS, QFD, brainstorming and morphology charts have been reviewed, and it has been established that such processes, along with competitor analysis and risk assessment, will aid in the success of the design project. Relevant British Standards have also been reviewed, and must be conformed to by any prototype training aids developed within this study.

Product liability must be considered, engineering calculations must be performed to assess the suitability of components, documentation of safety testing must be produced before any human testing is permitted (Arnold, 1991), and ethical clearance must be sought from the appropriate authority (Loughborough University).

Finally the training aid must be suitable for a range of gymnasts, considering both size and ability, and it must also provide a form of feedback to the gymnast in order to obtain the skill. Krogman (1972) also explains that due to the patterns of human growth, it should be possible to develop a single training aid suitable for both males and females from the age of six to sixteen, as body proportions and growth patterns are similar.

The following chapter will provide information about which gymnastics skills have been chosen, and what process was undertaken in order for them to be chosen. A further literature review specific to these skills will also be detailed.

3

Skill Selection and Preliminary Design Considerations

3.1 Introduction

The purpose of this chapter is to explain the choices made when deciding upon which gymnastics skills the training aids should be designed to assist. The criteria on which the decisions were made, and the relevance to the research will be discussed within the following sections. A concise literature review of the two chosen skills will then be presented.

In order to establish which skills were most suitable for the study a survey was conducted among nationwide International and High Performance coaches, and elite senior gymnasts, asking details such as which skills were critical to the development of an elite gymnast, which skills were most time consuming for coaches, and which skills needed to have a training aids designed to assist in their learning. This survey was critical to the project as it not only helped identify which gymnastics skills were suitable for this study, but also identified customer wishes and requirements which would later be used in the construction of requirement trees as a preliminary stage of the product design process. Various elite level gymnastics training sessions were also observed in order to determine which skills were most commonly taught and how they were taught, which skills were highly dependent on coach support and how this was provided, which skills required the most repetition or training time, and which training aids or equipment set-ups if any were used within the sessions. During these sessions the resident High Performance coaches were approached and their opinions sought on the same topics as were discussed in the survey. In total nine questionnaires were answered by International and High Performance coaches.

With information collected from the literature reviewed, from the conducted survey, and from further knowledge obtained from the observed elite training sessions, the generic requirements of a gymnastics training aid will be established, customer needs will be evaluated, and existing competitor equipment will be analysed. From the literature previously reviewed, a design method has been constructed (Figure 3.1) and is modelled on the product design process detailed in Wright (1998) (Figure 2.2 in Chapter 2). The

design of a training aid is considerably different from the design of other products, because it is crucial that the mechanisms used in learning a skill must be taken into consideration. For sports training aids this also requires considerations of the learning of the physical component of the activity which an athlete is attempting to acquire. This design path will be followed through the progression of the investigation. The first task is to determine the chosen skills, and to investigate any respective training aids which exist to help teach these chosen skills.

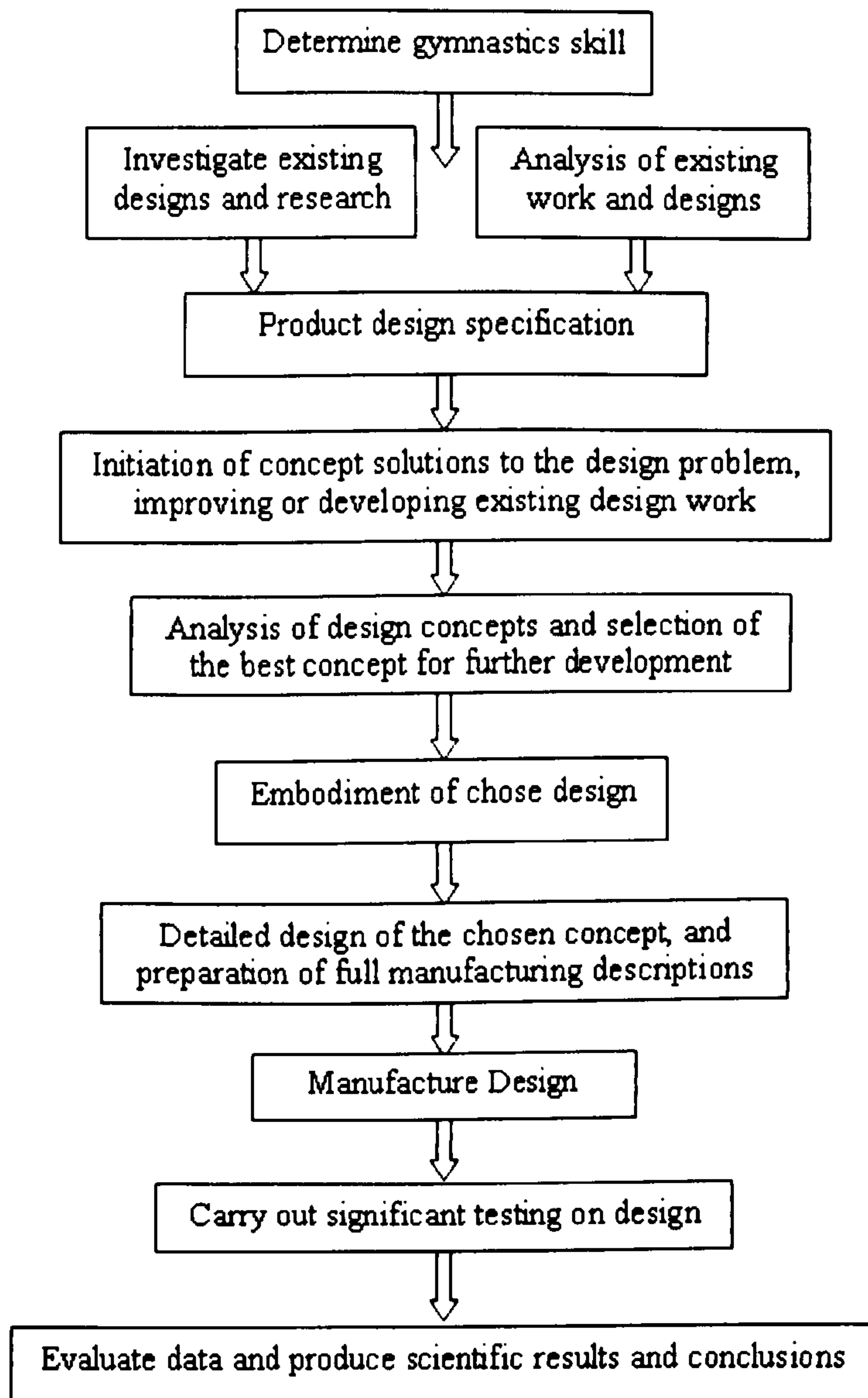


Figure 3-1: Design process for a gymnastics training aid.

3.1.1 Initial research of gymnastics skills

To ensure that the study addressed the wide range of gymnastics skills, it was decided that two contrasting gymnastics skills should be chosen: one involving balance

control, and the other involving dynamic movement, hence covering the two main types of gymnastics skills. This choice would not only encompass all general gymnastics activities but would also utilise a variety of data collection and analysis techniques due to the diverse nature of the chosen skills.

It was important that the study was also relevant within the area of interest: the field of gymnastics skill learning and skill acquisition. To ensure that the training aids to be designed were suitable with respect to gymnast development, several International and High Performance coaches and elite senior gymnasts were surveyed, elite training sessions were attended and observations were made, resident high Performance coaches were consulted, and equipment and training aids used within sessions were monitored. Resulting from these studies, several gymnastics skills were identified, and of these movements several were for training skills very specific to ability, gender and discipline: for example the Tkatchev on the asymmetric bars. Some of the identified activities were simply too basic to warrant any scientific investigation: for example a device to stretch hamstrings, whereas others were deemed suitable for postgraduate research purposes. A list was then compiled of those coaches' requests considered relevant for academic study so that further decisions on which ideas to take forward could be reached:

1. Backward long-swing (especially on Parallel bars)
2. Handstand on rings
3. Tkatchev on asymmetric bars
4. Float upstart
5. Development of the pommel horse 'bucket'
6. Backward handspring
7. Development of the somersault harness

The activities for which the training aid was to be designed were also required to coincide with the current gymnastics equipment market. It was important that the skills for which the training aids were to be designed were 'key skills' in gymnastics, and that the training aids could cater for a broad spectrum of gymnasts including various ages, abilities, genders, and if possible the training aid was to be multi-disciplinary so that the product would cover as much of the market demand as was possible with a single training aid.

With a set of suitable skills compiled from the various surveys and observations mentioned previously, the final decision as to which two training aids were to be designed was established through a final survey which was carried out on the National Gymnastics Squad coaches. The survey listed the various previously identified skills, and from this list the coaches were asked to select in their opinion the two most important skills for

gymnastics training, giving reasons and identifying if they thought a training aid would be suitable for their selected skills. The conclusion of this survey was that the two chosen gymnastics skills for which the training aids would be designed were:

- (1) The handstand on rings
- (2) The backward handspring

Results

Results from the survey showed that 100% of the Men's Artistic coaches wanted a device to train a rings handstand, and that the handstand on the rings was the most favoured type of handstand on apparatus. It was also shown that 89% of coaches wanted a backward handspring trainer, and only 22% of the coaches thought that there were any other useful training aids for the backward handspring. Further results from the surveys will be discussed in the Sections 3.2 and 3.4.

3.1.2 Handstand on the rings – skill information

The handstand is a stationary balancing skill, which requires significant body control and upper-body strength, especially when performed on the rings. It requires the gymnast to balance on his hands on two moving pendulums, which involves the gymnast controlling multiple movements. A complex control strategy has to be learnt in order to stay in balance during a handstand on the rings. Although not of a high level of difficulty, the handstand on rings is a hard skill to master, and one that a young male gymnast must learn if he wishes to become elite (Mitchell et al., 2002).

As several training aids are already available on the market, it is evident that there is demand for a training aid to assist the learning of the handstand on rings. However according to the information collected during the research, none of the existing training aids are considered suitable by the surveyed High Performance coaches. Some of the main problems found with the existing training aids were identified by the survey, such as the equipment not replicating the technique used on the rings. Such details will be discussed in greater depth within Section 3.4 during the detailed competitor analysis. It will be important that these issues are addressed and be removed from any new training aid developed within this research project.

3.1.3 Backward handspring – skill information

In contrast to the rings handstand, the backward handspring is a dynamic movement. It is a key skill in gymnastics, and is performed in Women's and Men's Artistic gymnastics, in Sports Acrobatic gymnastics, in Tumbling, in Team gymnastics, and in General gymnastics. It is performed as a single skill and as part of a sequence on the beam, and is an integral component of most tumbling and dynamic sequences. It can also be found as a component of performed vaulting skills, such as the Yurchenko, and as part of various Sport Acrobatics tempo skills.

'The backflip, along with the round-off may well be the most important skill a gymnast ever learns' (Warren, 2003).

This skill is often one of the first backward dynamic movements a gymnast will ever learn, and so takes a long time to master properly. Mastering the skill involves a lot of 'hands-on' work from the coach, shaping and supporting the gymnast in the different learning phases of the skill. As the skill is used widely, and as it has been established to be of extreme importance in gymnastics, it is an ideal skill to design a training aid for. When teaching the skill to older gymnasts, the set-up may also require a great deal of equipment: for example, trampette and multiple matting just to support a single skill. In general gymnastics clubs it is frequently the case that equipment is scarce, and so having a training aid which could safely and correctly support the gymnast would be of a great advantage to such clubs, allowing the standard equipment to be used for other purposes.

Although at least three training aids already exist for the backward handspring, the results from the survey show that none is adequate to fully aid the coach and gymnast in mastering the skill. Further details on the results of the survey will be discussed in the following section, and in Section 3.4 during the detailed customer analysis.

3.2 Requirements

From the survey carried out on nine of the UK's most highly qualified coaches, it was established that there were several problems and flaws with the existing training aids designed to assist the learning of the handstand on the rings (Figure 3.2) and the backward handspring (Figure 3.3). To ensure the success of this research study, it was essential that the problems with the existing training aids must be identified to prevent any replication of these design flaws in the development of the new training aids.

Figure 3.2 below, describes the most commonly identified problems with existing training aids designed to assist in the learning of the handstand on the rings. There were only two main issues identified but both were significant shortcomings of the existing equipment available on the market. The fact that the existing training aids do not encourage the gymnast to physically replicate the same actions and control strategy as that required to hold a handstand on the rings is obviously a serious problem. If a training aid does not correctly reproduce the physical requirements of the actual skill the training aid is ineffective.

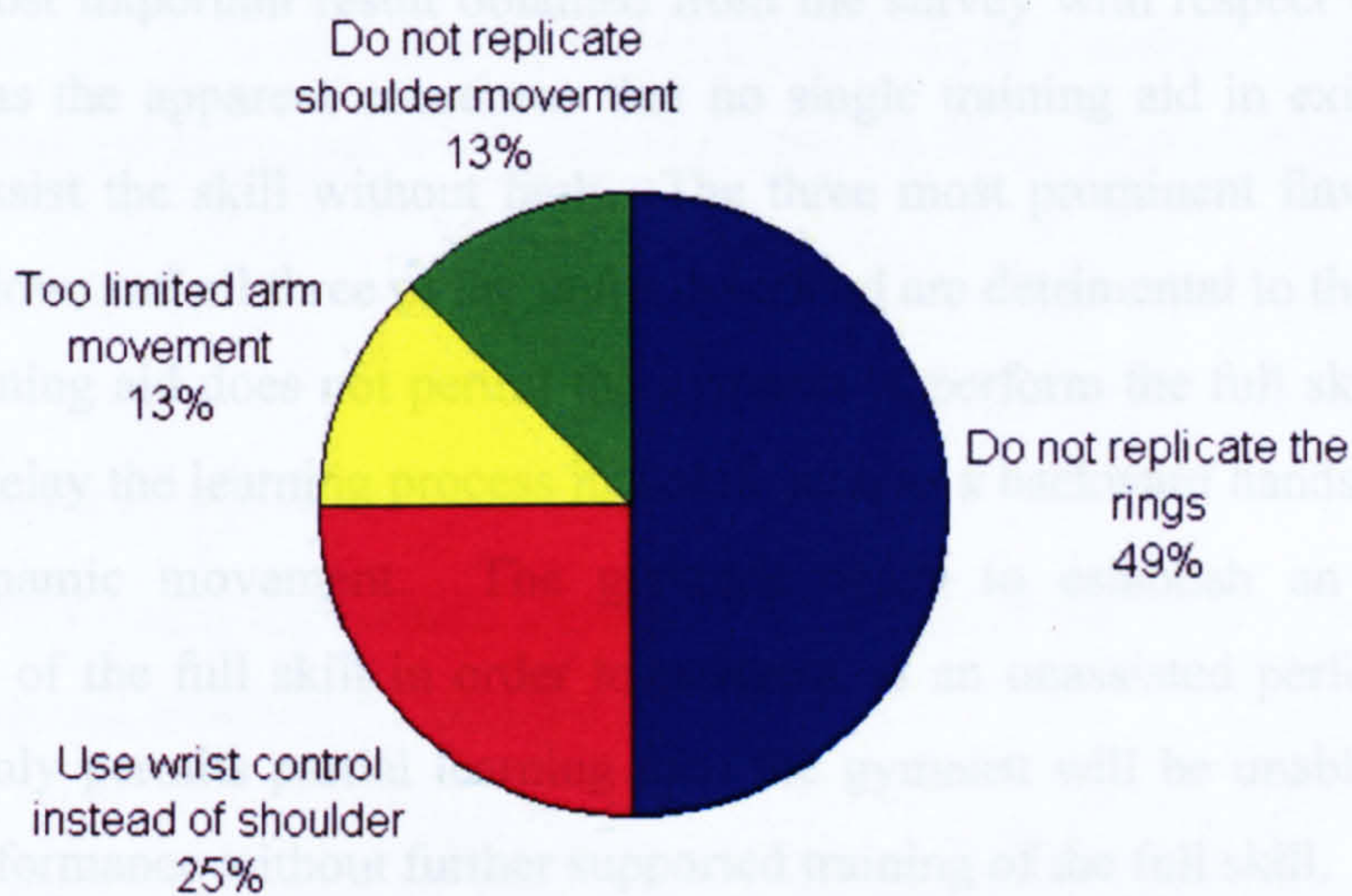


Figure 3-2: Survey results of problems with existing rings handstand training aids.

The other main problem with the present training aids for the handstand on rings is that most of them recruit a wrist control action. To maintain balance during a handstand on the rings a gymnast is required to lock the wrists in position and use small controlled changes in the shoulder angle to keep the mass centre of the body over the support point, which is the hands on the rings. If a gymnast tried to recruit a wrist control action whilst balancing a handstand on the rings then he would simply fall from the handstand. It is not possible to produce enough movement just through the wrist to retain balance on the rings, and unlike on the floor, on the rings there is no solid surface against which horizontal reaction forces can be induced. Hence moving the wrists would not induce any opposing torques to correct the position of the body to retain a balanced position.

A gymnast will learn a handstand on the floor before venturing on to performing this skill on the rings. This will mean that the gymnast has a good understanding of the wrist control strategy used to maintain a handstand balance on the floor. If a gymnast is then placed on a training aid which encourages him to control his balance by using a wrist

control strategy, this will be far simpler for him to learn than the required shoulder control strategy as he already will have obtained the knowledge and understanding of the wrist control. Such a training aid is therefore preventing a gymnast from learning how to maintain a handstand balance on the rings.

It is important that any new training aid designed to help learn a handstand on the rings must encourage a rings control strategy to permit a gymnast to maintain balance whilst performing a handstand on the training aid. The training aid must also replicate the handstand as it is when performed on the rings.

The most important result obtained from the survey with respect to the backward handspring was the apparent consensus that no single training aid in existence has been designed to assist the skill without fault. The three most prominent flaws are shown in Figure 3.3. below, and all three of the faults described are detrimental to the learning of the skill. If a training aid does not permit the gymnast to perform the full skill then this will significantly delay the learning process in a skill such as a backward handspring which is a fluid and dynamic movement. The gymnast needs to establish an awareness and understanding of the full skill in order to progress to an unassisted performance. If the training aid only permits partial learning then the gymnast will be unable to progress to unassisted performance without further supported training of the full skill.

3.3.1 Handstand on the rings

Coaching

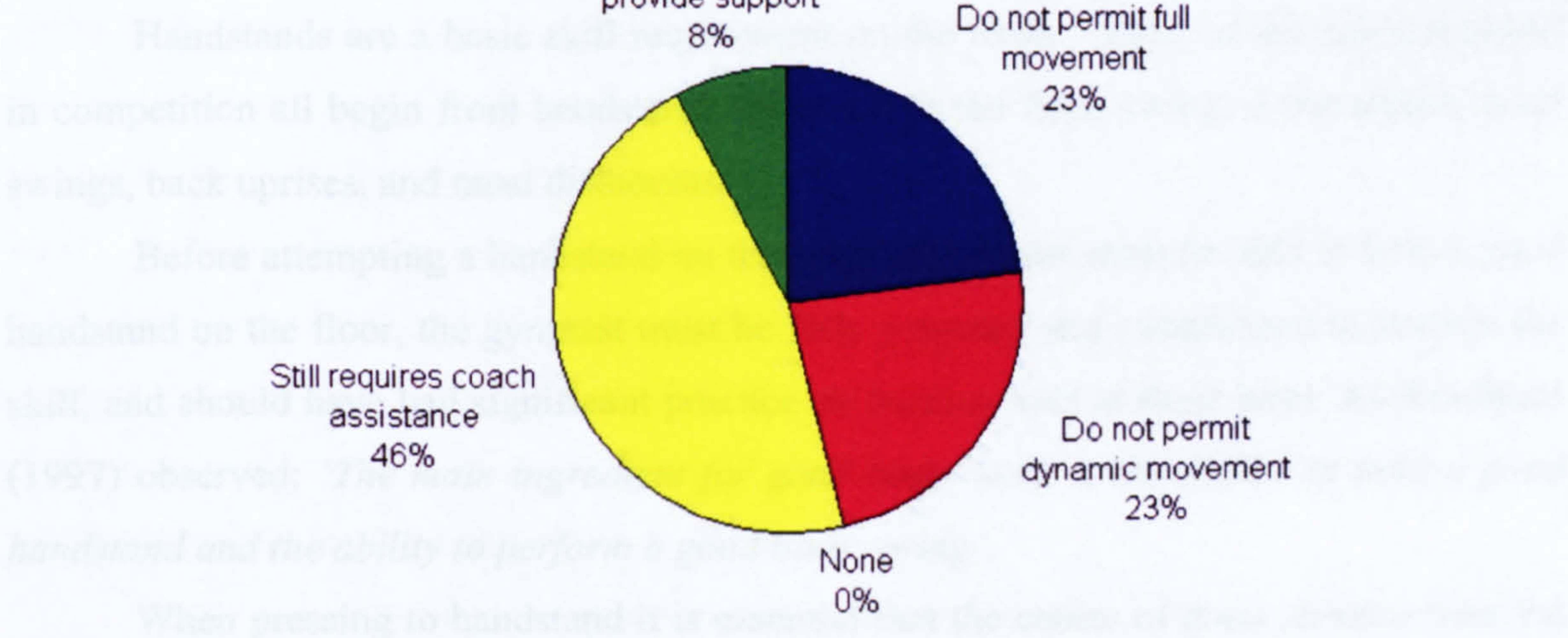


Figure 3-3: Survey results of problems with backward handspring existing training aids.

Some of the training aids available on the market also do not permit the gymnast to perform the skill with the same dynamic nature that they will require to perform the skill unassisted. This is a serious problem as training aids are supposedly designed to assist in

the learning of the skill, and progress a gymnast to a state where they can perform the skill unaided.

The final flaw highlighted by the survey was that the existing training aids still require the assistance of a coach: for example the harness. The importance of this flaw, however, is dependent on the reasons for using the training aid. If the device is to aid with the support of the skill, then the requirement of the coach's assistance is not a problem. However, if it is intended that the training aid should permit the gymnast to perform the skill alone in a safe and technically correct manner, if this training aid physically requires a coach be present during its use then the training aid becomes obsolete. In this situation the coach may as well simply provide the normal support to the gymnast himself.

3.3 Literature review of the chosen skills

A review of skill techniques, details of coaching points, supporting methods, and existing training aids will now be detailed.

3.3.1 Handstand on the rings

Coaching

Handstands are a basic skill requirement on the rings. Many of the skills required in competition all begin from handstand, for example the felge swing to handstand, giant swings, back uprisers, and most dismounts.

Before attempting a handstand on the rings, a gymnast must be able to hold a good handstand on the floor, the gymnast must be fully prepared and conditioned to attempt the skill, and should have had significant practice on training aids at floor level. As Readhead (1997) observed: *'The main ingredient for good rings work is the ability to hold a good handstand and the ability to perform a good basic swing'*.

When pressing to handstand it is essential that the centre of mass remains over the point of support (the hands) throughout the skill, and it is important that the gymnast does not lose the correct body shape during the press (Figure 3.4). As the gymnast reaches handstand, it is required that the gymnast fully extends the arms, and turns the rings slightly outward; the entire body should be straight with shoulders locked out (Fukushima and Russell, 1980). Crumley (2000) comments, however, that the angle through which the

wrists are rotated outward should not exceed 45° . The arms and shoulders should be clear of the ring straps to allow the handstand to be balanced freely.

It is possible for this skill to be practised on low rings by the gymnast kicking off a platform and trying to stop in handstand. Initially a gymnast should have a coach to stabilize the rings and to steady the feet on the ring-wires. When the gymnast achieves the handstand position he must be encouraged to practice holding the handstand position for progressively increasing periods of time (Readhead, 1997).

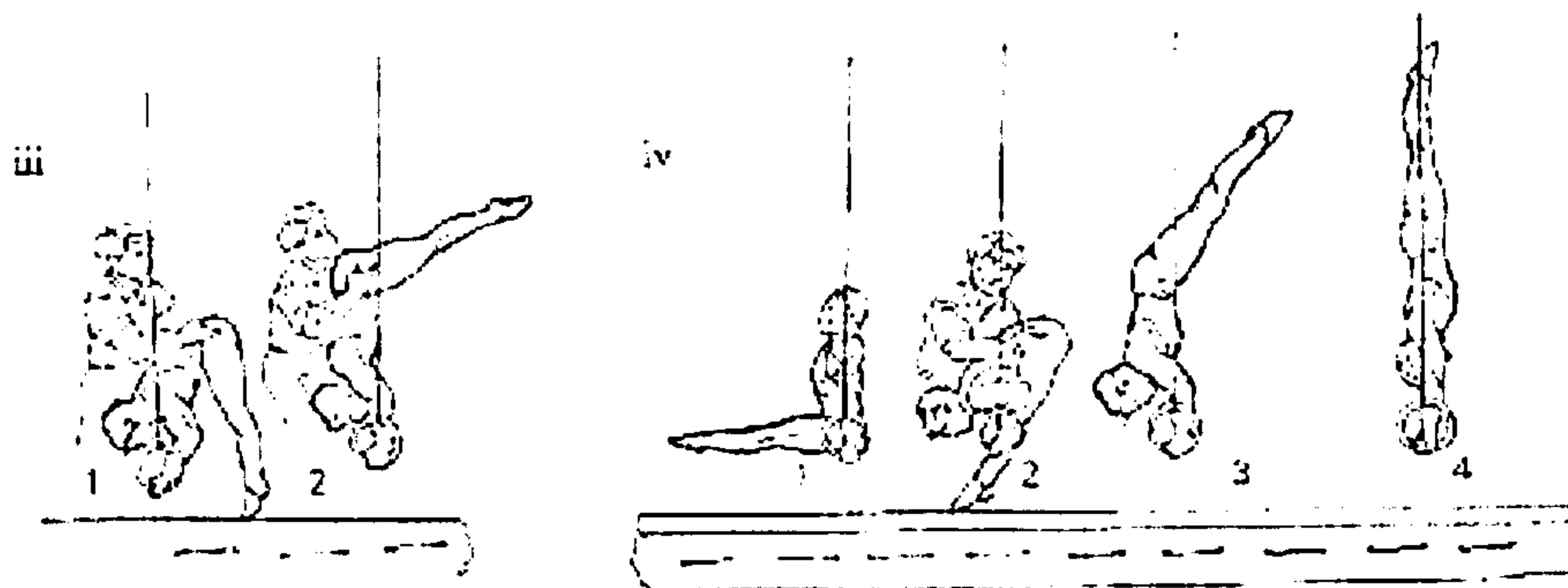


Figure 3-4: The bent body press to handstand (adapted from Readhead, 1997).

Biomechanics

For a handstand to be achieved on the floor, the mass centre should remain vertically above the base of support in order to prevent falling. When performing a handstand on the floor, when out of balance, the mass centre is transferred back over the centre of the base of support by engaging muscular torques mainly at the wrists, but also at the shoulders and hips (Yeadon and Trewartha, 2003). When performing a handstand on the rings, however, the wrists remains fixed and in line with the rest of the arm (Readhead 1997). It is the shoulder torque that controls the balance, and rather than the mass centre being transferred back over the centre of the base of support to retain balance, a handstand on rings requires the hands to be moved back under the mass centre. The mass centre in fact has minimal movement during this skill: it is the hands that move, which is opposite to the handstand on the floor (Sands et al., 2003).

There is increasing evidence that the control system for equilibrium includes at least two subsystems. Zatsiorsky and Duarte, (2000) state that the central nervous system specifies an intended position of the body, and that this intended position is specified by a reference point on the supporting surface with respect to which the body equilibrium is maintained. From their work there is increasing evidence during quiet stance that the body sways for two reasons: the migration of the reference point, and the deviation away from that point. This corresponds in a handstand to the movement of the mass centre over the

base of support (the hands). Yeadon and Trewartha (2003) discuss that the control of the mass centre position in a handstand is achieved by the generation of a series of muscular actions that work to produce torques about joints that maintain various body configurations controlling the movement of the mass centre (Figure 3.5).

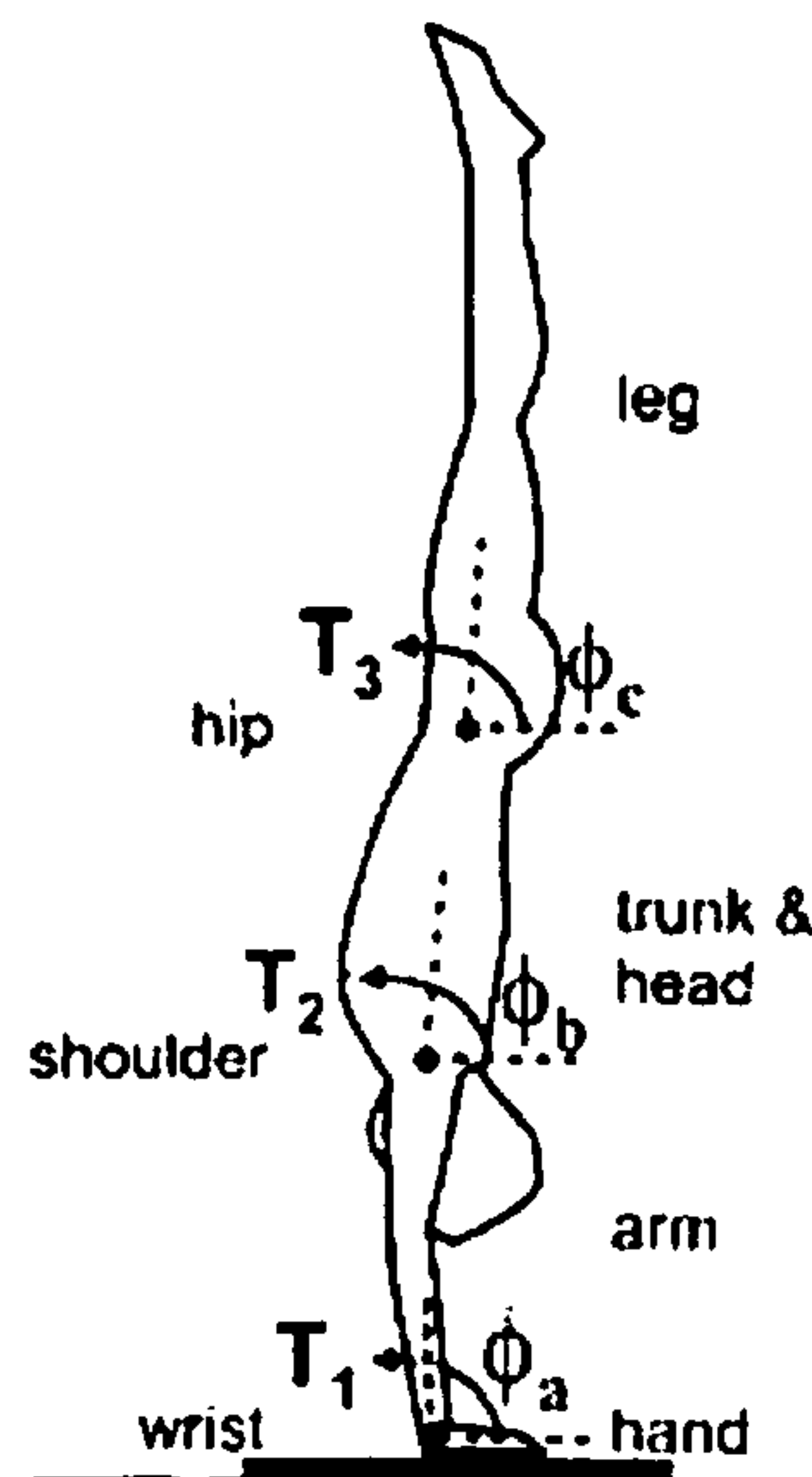


Figure 3-5: A representation of a gymnast in a handstand (adapted from Yeadon and Trewartha, 2003).

Stationary stance uses a similar control technique to a handstand, except the stance is inverted. Posture, the position and orientation of the body segments, and balance, the control of the centre of mass or centre of pressure position are coupled. Most postural adjustments change the mass centre location to retain balance (Riley et al., 1990). The centre of pressure (COP) is a fictional point similar to the centre of mass. It is a summation of all of the forces produced by contacting objects. For the example of stance, the COP may not always lie under the feet or under the path of the foot which is in contact with the ground. It is from this point that the resultant ground reaction forces are established. Postural sway is always present during the balance, no matter how still it may appear. Active control is required during quiet stance as body sway results in forward, backward and side-to-side movements of the COP (Kodde et al., 1982; Carroll and Freedman, 1993) and similar activity can be observed in a hand balance.

Chaos can be defined as the occurrence of a high degree of irregularity in a deterministic non-linear system. In chaotic dynamics, randomness emerges out of deterministic dynamics. Chaotic sway may be found in the movement of the COP during quiet stance with active swinging of the upper limbs (Yamada, 1995). This is equivalent to the control required during a handstand on the rings when the legs begin to move vigorously when out of balance. It is thought that chaotic swaying of the COP, observed

when the subject is standing still, plays an important role in the adjustment of posture (Yamada, 1995). In work carried out on balance control with relation to mass centre velocity and position (Pai and Patton, 1997), it was found that both strength and friction were limiting factors of balance control during movement. As surface friction decreased, more strength was required to maintain a static position. Relating this concept to a handstand on rings possibly suggests that with no opposing frictional forces at the hands, any postural changes will require more strength to maintain balance than a handstand on the floor would due to the frictional forces present between the hands and the floor.

In upright stance, the movement of the COP is sensitive to rotation about the ankles, hips and at the shoulders, with this sensitivity being greatest to ankle rotation, less to hip rotation and least to rotation at the shoulders. Most of the torque necessary to stabilise upright stance must be generated about the ankles (Koles and Castelein, 1980). It is therefore possible to compare the ankle rotation observed in the work by Koles and Castelein (1980) to the movement of the wrists during a handstand on the floor. However during the handstand on rings, the wrists are locked, with the hands and wrists becoming a rigid extension of the arm, hence rotation of the wrists are not involved during a handstand on the rings. In this situation the shoulders would be considered to be the joint nearest to the rings. In accordance with the work of Koles and Castelein (1980) this would suggest that the shoulders perform the greatest control of the handstand balance on rings as they are the joint closest to the base of support. However further work would need to be carried out to confirm that the shoulders are the main contributor to balance control during a handstand on the rings.

External vibrations can affect bodies during quiet stance, however, visual information reduces these effects but is insufficient to suppress them completely (Hayashi et al., 1981). Relating this to inverted stance: during the handstand on rings the head is orientated such that vision can be partially obstructed; vibrations of the rings frame could therefore produce a significant effect on the control of the hand balance, which would not generally be experienced when performing the same skill on the floor. However, it has been concluded in work studying the effects of impaired vision on balance that gymnasts are able to use remaining sensory modalities to compensate for the lack of visual information in unstable postures (Vuillerme et al., 2001). Expert gymnasts are trained to maintain and restore both static and dynamic balance in challenging conditions (Vuillerme and Nougier, 2004). This training will occur through repetitions of skills and through being constantly in an environment which requires this type of multi-sensory control.

The handstand on rings has several possible degrees of freedom with regards to the movement of the gymnast's arms in the transverse plane (parallel to the floor) (Figure 3.6). However there are six main extra degrees of freedom of movement compared to a stationary floor handstand that need to be considered. Firstly the arms can move back and forth separately, opening and closing the shoulder angle along the sagittal plane, (x -displacement). The main movement to control is the hands moving away from each other sideways, along the frontal plane (y -displacement). Finally the wrists can rotate and the arms twist either outward or inward around the long axis of the arm (rotation about the z axis).

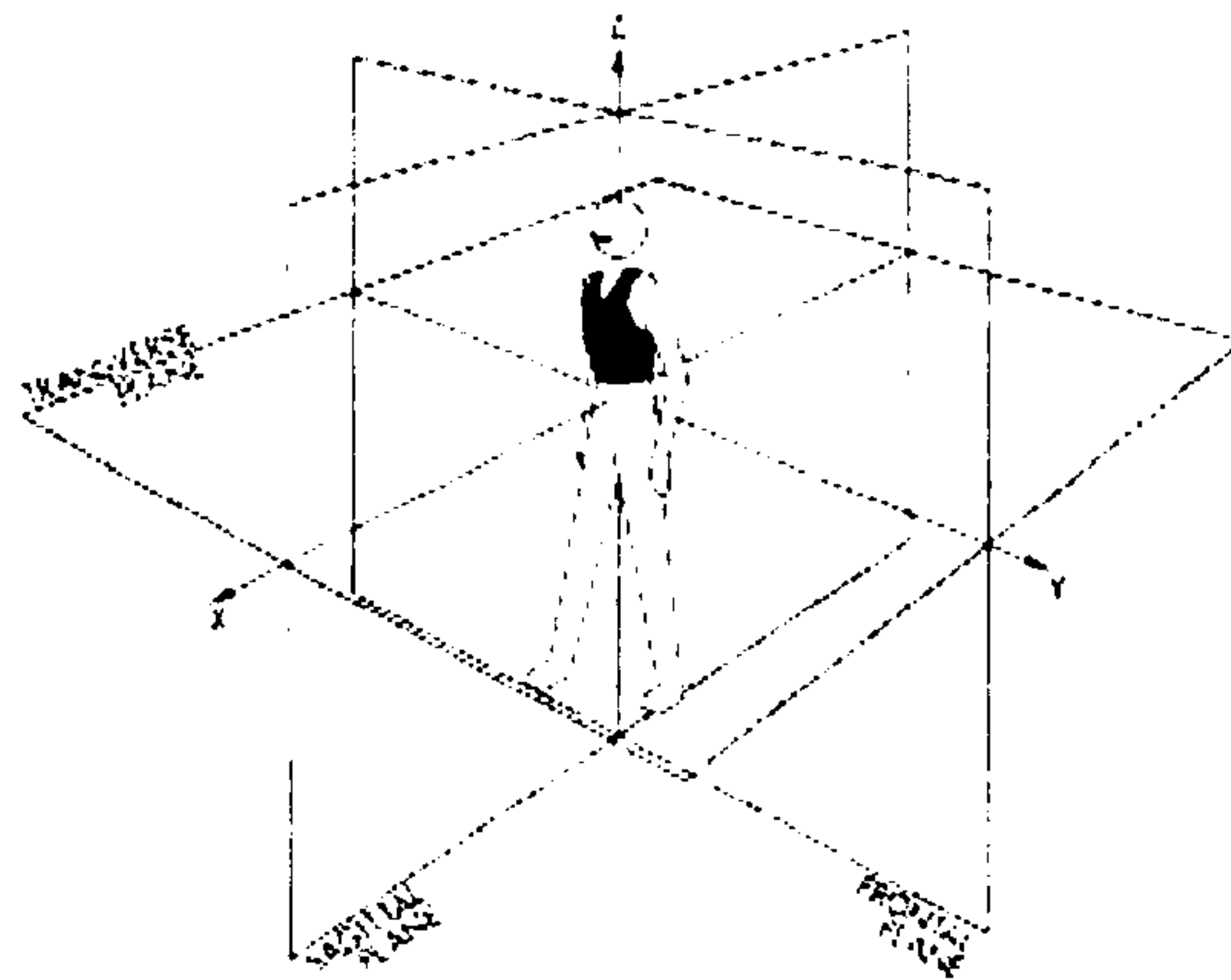


Figure 3-6: The basic anatomical position (adapted from Gluck, 1982).

Incorrect Technique and Resultant Problems

The main problems encountered when performing a handstand on the rings generally all originate from a lack of strength and ability to control the balance. Crumley (2000) explains that the two main objectives when learning a handstand on the rings is strength and balance. Lack of wrist strength, arm strength, and body tension can lead to the gymnast leaning his wrists on the rings, and his slightly bent arms on the rings and cables.

Gymnasts sometimes have a tendency to use the abdominal muscles rather than the shoulders to maintain balance. This can result in the gymnast struggling to maintain the straight, tight handstand and lose body tension. Over-compensation for loss of balance can produce large movements of the hands, resulting in a struggle to regain any state of balance, and this will be exaggerated by a lack of body tension.

Existing Training Aids

After a handstand on the floor, there are several different training aids available to train a handstand on the rings. The first to be discussed introduces a single new degree of

freedom into the handstand control mechanics. This piece of equipment is called a handstand swing (Figure 3.7). The equipment introduces movement back and forth through the frontal plane and is based on a rocker mechanism. The ergonomic position of the grips is supposed to encourage a correct positioning of the hands, and is stated by Janssen Fritsen (2003) as being capable of incorporating a variety of shoulder widths. This however is doubtful, as if the hands are not in the centre of the grip, then the mass centre is not over the centre of the rocker, and this may lead to a unstable balance. Although the training aid does introduce some movement into the balance, as there is friction between the swing and the floor, and as the training aid is only capable of rocking back and forth it may encourage some wrist control. The training aid therefore does not replicate the control technique required to hold a handstand on the rings. It more closely replicates a handstand on the floor. Also as the rings move through the frontal plane they will follow a slight arc. However this arc is the inverse of that of the handstand swing, curving up as the displacement increases rather than dipping down towards the floor as the handstand swing does. This will also not help the gymnast to learn the correct control technique for handstand on the rings.

A development of the handstand swing training aid is the handstand bowl (Figure 3.8). This is similar to a handstand swing, involving the same grip frame, but located in a bowl rather than on a rocker, thus introducing a further degree of freedom. The bowl allows any movement in a 360° orientation within the x-y plane, training control of circular motion as well as the rocking motion introduced by the handstand swing. The movement in all directions increases the degree of difficulty (Janssen Fritsen, 2003).

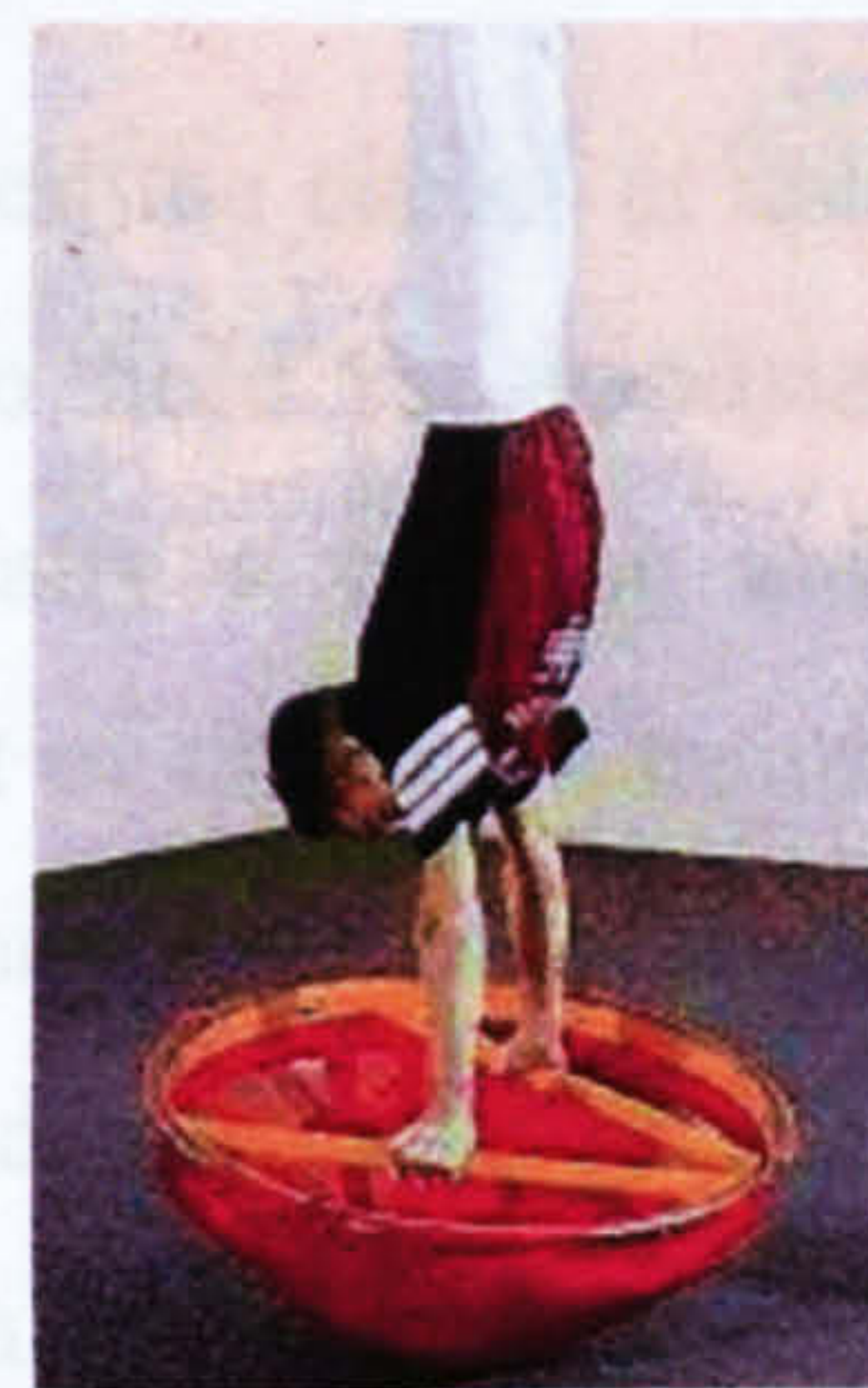


Figure 3-7: Janssen Fritsen Handstand swing.

Figure 3-8: Janssen Fritsen Handstand Bowl.

As with the handstand swing, it is still possible for the gymnast to use wrist control during a handstand hold on this training aid, and the directions of the tilt of the apparatus

again are the opposite to that of the rings. This training aid may permit the gymnast to learn to hold a handstand on an unstable surface, but will not encourage the technique necessary to perform a handstand on the rings.

The next training aid is two small separate handstand bowls (Figure 3.9) allowing the two arms to move totally independently of each other. Due to the independent movement of both hands, Janssen Fritsen (2003) claims that the real situation of the handstand on the rings can be simulated. Out of all three of the training aids so far discussed, this training aid will most encourage a wrist control technique which is incorrect for rings. Also when the bowls rock towards and away from each other this introduces wrist flexion and extension, a motion that would initiate a fall from the rings. The final and main training aid is the rings themselves, but low to the ground, either suspended from a lower frame, for example the parallel bars, or standard rings with lengthened cables (Figure 3.10).



Figure 3-9: Janssen Fritsen Mini Bowls.



Figure 3-10: Janssen Fritsen Rings for Parallel Bars.

The rings can also have a strap placed between the cables at ankle height to allow the gymnast to rest his feet on while he trains to hold the handstand (Figure 3.11). Although more a training technique than specifically a training aid, it more closely replicates the handstand on the full rings frame best of all of the training aids discussed, but it still does not exactly replicate the full skill. The length of the cable has a significant effect on the control required to hold the handstand. A cable of infinite length would permit the most movement of the wrists away from the mass centre whilst remaining in balance, and therefore make the skill simpler. With short cables, a small forward movement of the wrists produces a large cable angle which resultantly accelerates the mass quickly backwards. Therefore, the short cables on the training aid in fact increase the difficulty of the skill, and most definitely train a different technique to the full rings.

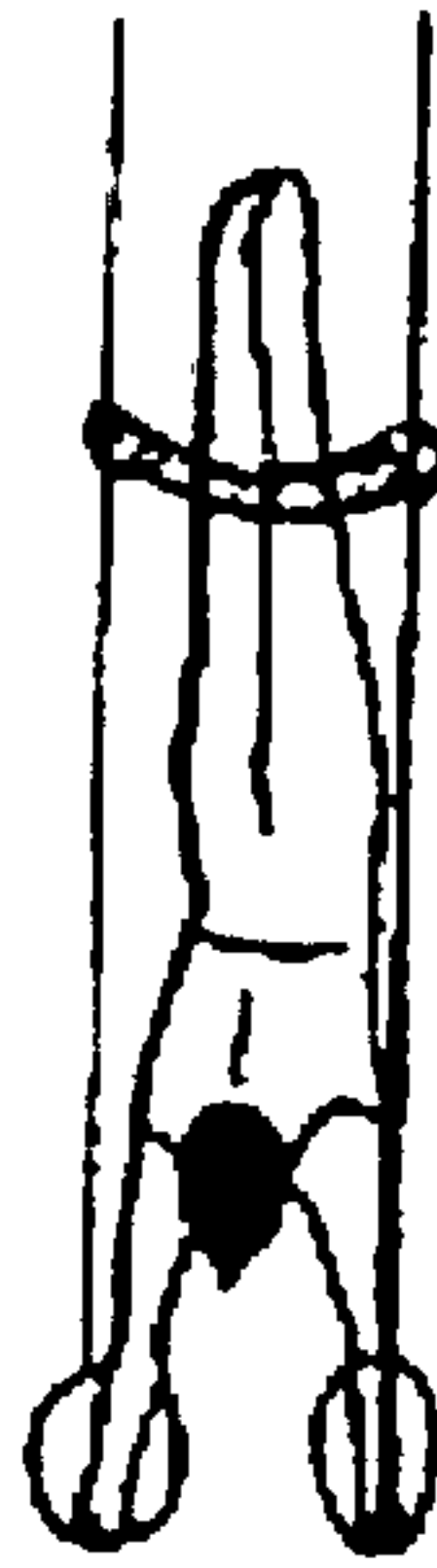


Figure 3-11: Rings handstand with a supportive strap (adapted from Russell, 1980).

Rings Handstand Summary

From the literature reviewed, it has become apparent that as friction decreases, more strength is required to maintain balance (Pai and Patton, 1997); it can therefore be surmised that the handstand on the rings is a physically more demanding skill than a handstand on the floor. If changes in shoulder angle perform most of the control, then the hands must be provided with adequate space in which to move, and this will need to be established through the analysis of the handstand on the rings.

A training aid for the rings handstand must replicate the 'real' environment experienced by the gymnast whilst performing the skill on the rings. The training aid must therefore provide a frictionless environment in which the skill can be practised. Though it may not be possible to replicate vibration of the rings frame, the training aid must still respond to tiny movements produced by the gymnast. All six degrees of freedom must be available to the gymnast to enable him to control the balance correctly. However the control should not involve wrist joint movement. It should be possible for gymnasts with a variety of shoulder widths to use the training aid, and it must provide sufficient space for the movement of the wrists.

As lack of strength can be an issue with the progression of this skill, progressive learning will enable the gymnast to gain strength and understanding in parallel, by learning the skill in stages whilst progressing toward the performance of the full skill. In terms of the design of the training aid, data must therefore be obtained in order to understand the magnitudes of movement involved during the control of a handstand on the rings. In addition, a review of previous rings studies will be carried out in order to identify any other data types which should be collected.

Data Collection

In most of the studies, as in much biomechanical research, both video and kinetic data were collected. The collected kinetic data was often in the form of accelerometer or force plate data. Force plate data was collected for a handstand on the floor (Yeadon and Trewartha, 2003) but this technique would have some inherent difficulties if it were to be used for a handstand on the rings. A different type of force transducer would be required to collect force data from the rings, as the cables from the rings frame suspend the gymnast above ground level. Such transducers have been used in a study by Brewin et al. (2000) during which a specially constructed rings cable was used to collect force data during a backward giant circle. The rings cable was used in series with a calibrated Kistler quartz force link (9331A) in order to obtain a measurement of cable tension during the skill.

Conclusion

For the study of the rings handstand training aid, it has become apparent from the literature reviewed, that a study of the handstand on the rings must be performed in order to design a training aid which will replicate the same balance control mechanism during performances. To enable this: kinetic data must be collected to establish what forces are present during the skill on the rings; motion data must be obtained to gain insight into joint centre movement and body configuration during the balance; muscle data should be collected to evaluate muscle activations. This data should then be compared with data from a performance of a handstand on the prototype training aid to ensure that the handstands utilise the same control techniques.

3.3.2 Backward handspring

Coaching

The backward handspring is a dynamic movement during which a gymnast will jump over backwards from their feet onto their hands, and then from their arms back onto their feet (Warren, 1976).

There are several different types of backward handsprings, depending upon the goal of the performance. Two major types are easily discernible: one used as a separate skill for transition (the floating backward handspring), the other used as an accelerator preceding tumbling combinations (Figure 3.12).

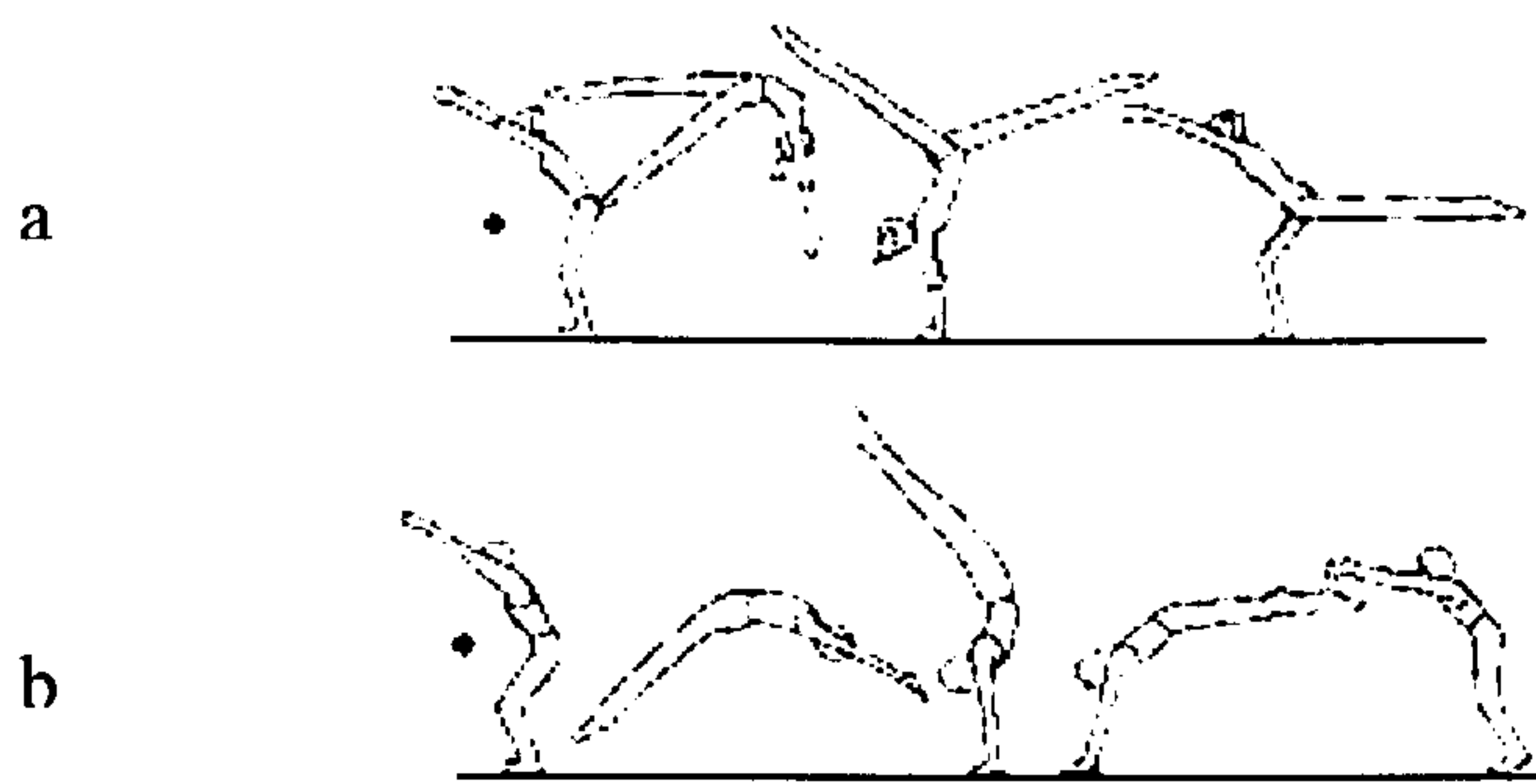


Figure 3-12: (a) Floater backward handspring, (b) Accelerator backward handspring (adapted from Gluck, 1982).

Each type exhibits a different movement pattern and has variables which are maximized to improve performance. The *floater backward handspring* requires maximization of the height of the centre of gravity (CG) of the gymnast, while the accelerator requires maximization of horizontal linear momentum of the CG. The maximization of height in the accelerator backward handspring represents a sacrifice in horizontal linear momentum (Gluck, 1982b).

In general a gymnast will learn a standing *accelerator* backward handspring first. A standing backward handspring is performed from a stationary start, and although rarely used in isolation (except during learning), the standing backward handspring is the skill in which most beginners experience their first lead-up to the advanced acrobatic skills. From the first attempt, a young gymnast must have absolute confidence in the coach, since this movement can have dangerous consequences if done incorrectly (Mitchell, 2002). Most gymnasts prefer initially to be slowly lifted over backwards, from a standing position with arms held overhead and lowered into a handstand position rather than experiencing the fully dynamic action straight away as this can be confusing and un-nerving (Hayhurst, 1980; Johnson, 1974).

When performed as a fully dynamic technique, the shape of the flight parabola will vary between gymnasts, depending upon the kind of takeoff performed. The gymnast must keep the fully-extended arms stretched well back to maximise the angle between the arms and the body. This is to prevent the gymnast from landing on his or her head, to prepare them for a firm support and the consequent push back onto their feet (Hayhurst, 1980).

Supporting skills in gymnastics does not always require guiding a gymnast through the entire skill. Providing assistance where most needed for a successful attempt, and for injury prevention is just as useful. A skill can be supported by hand contact from the coach, by a mechanical device such as a training aid or by using a spotting belt. For the backward handspring, it is possible to use large pieces of mat foam covered with a soft

material (Figure 3.13). The gymnast stands at one side of the foam block and performs the backward handspring over the foam. This is to alleviate fears of the gymnast falling on her head. If the gymnast's arms do collapse, then it is intended that the head hits the foam instead of the floor. This set-up can also help to prevent the bad habit of '*undercutting*' the backward handspring. If the skill is *undercut* the performance is high and short (loopy), with a small height to length ratio. With this set-up, the gymnast will be required to make the skill long enough to 'clear' the foam block, reducing the effects of any poor techniques (Cooper and Tranka, 1989; Brown and Wardell, 1980).

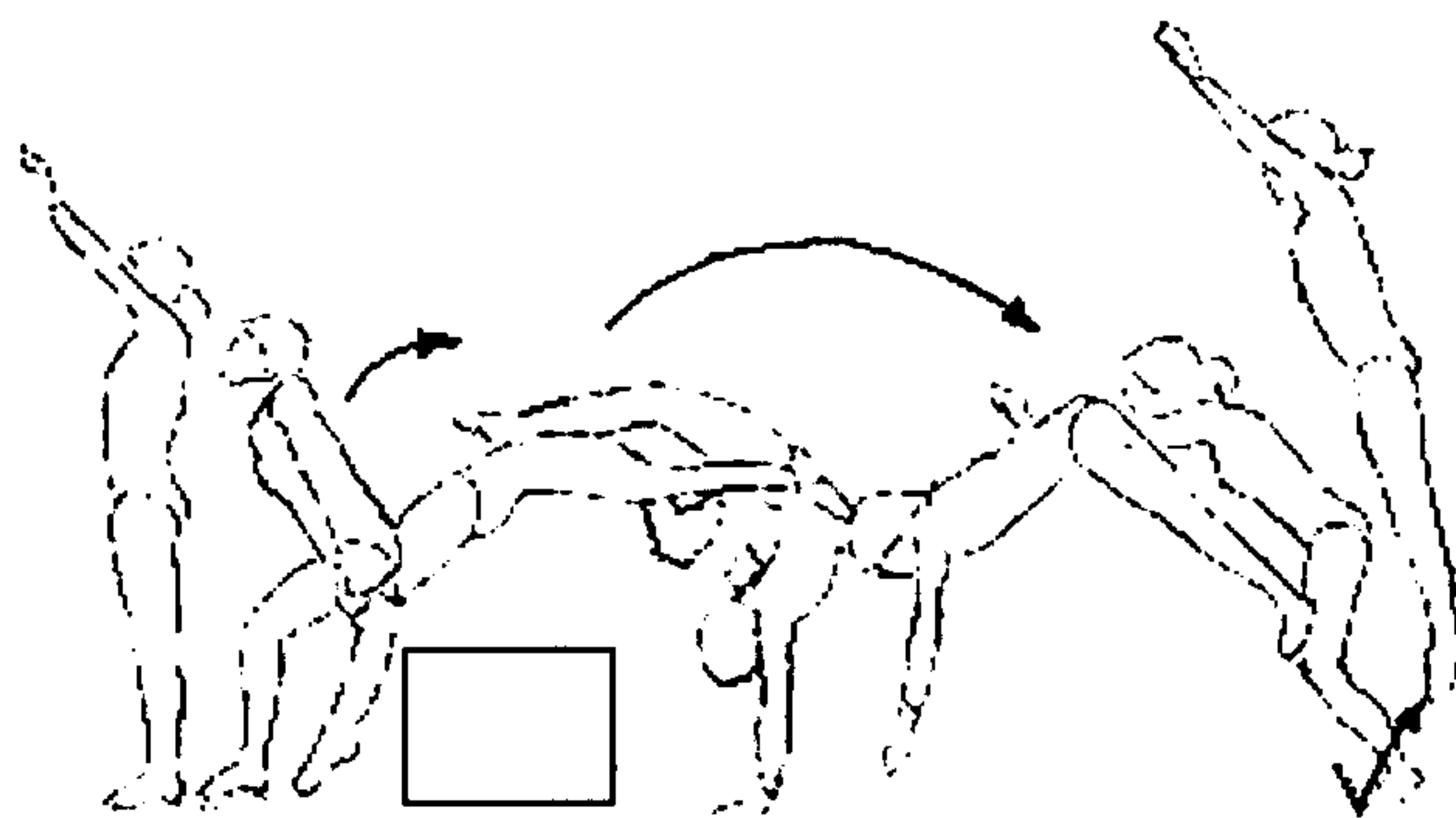


Figure 3-13: A foam block backward handspring training aid (adapted from Cooper and Tranka, 1989).

One of the main coaching points to ensure the desired execution of the backward handspring utilises a continuous and forceful back-upward lift of the arms, head, and chest (Low, 1993). This description can however be misleading, as it is the strong action of lifting the trunk that creates most of the rotation. The arms do add to the angular momentum of the movement, but also move up to the ears ready for landing and the head moves as it is attached to the trunk, and hence lifting the arms is the correct action to take. Boone (1976) states that the angular momentum derived from the arms is transferred to the body as they begin to slow down, and therefore aids the rotation of the skill, in agreement with Low (1993), and Conner (1992), stated that the effective use of the arms can make the difference as to whether the backward handspring is successful or not. However as stated earlier it is the trunk that produces the most angular momentum, but when a gymnast is told to use the arms more, they instinctively lift the chest as well as the arm swing leads the body into a hollow position (Low, 1993).

Boone (1976) also comments that it is necessary that the full flat feet of the gymnast push against the floor as the body becomes unstable to ensure maximum push and correct direction. During the full extension of the legs, the opening of the hip, knee and ankle joint angles moves the CG further from the base and drives the skill backwards as well as increasing its angular momentum. Finally as the hands contact the mat, the

shoulder angle should remain fully extended to provide a solid body configuration for the landing into the handstand position.

When hands make contact with the floor in the backward handspring, there should be a very slight arch down the length of the body to facilitate the 'snap' action. During this action the gymnast contracts her hip flexors, removing the arch from the body shape and changing her body configuration to slightly piked or dished, but maintaining a fairly straight body shape. According to Still (1990) the result of this action is to increase the angular momentum in the post flight, giving the advantage of a very quick rotation about the hands, helping the gymnast to stand up.

If the backward handspring is to be followed by a somersault, then the body finishing position will be different to when it is to be followed by another backward handspring (Gluck, 1982a). These resulting postural changes needed for another backward handspring to follow can be introduced by quickly closing the hip angle, initially bringing the legs in closer to the chest (leg snap), before then quickly re-opening the hip angle lifting the chest away from the legs, or by when the feet touch the ground, actively opening the hip angle, lifting the torso (torso snap). A proper snap down will start with the shoulder block, sending the hands off the ground (Bennett and Miller, 2001). Gluck (1982a) explains that if the leg snap of the backward handspring begins with hip and shoulders hyper-extension, the snapping action produces three major effects: the horizontal linear velocity of the CG is increased; the CG is raised; and the backward angular momentum is increased. If the leg snap occurs when the CG is vertically over the hands, then the CG is maximally elevated, while the linear and angular velocities will not be maximized. If the leg snap occurs slightly after the CG passes the vertical, then the CG height will not be maximized, but there is a proportional increase in the linear and angular velocities

Biomechanics

During a standing backward handspring, the centre of mass of the gymnast is required to be set off balance before the move can begin (Witten and Witten, 1983). By leaning backwards off balance the gymnast positions the CG outside of the base of support. This action initiates the beginning of the falling phase.

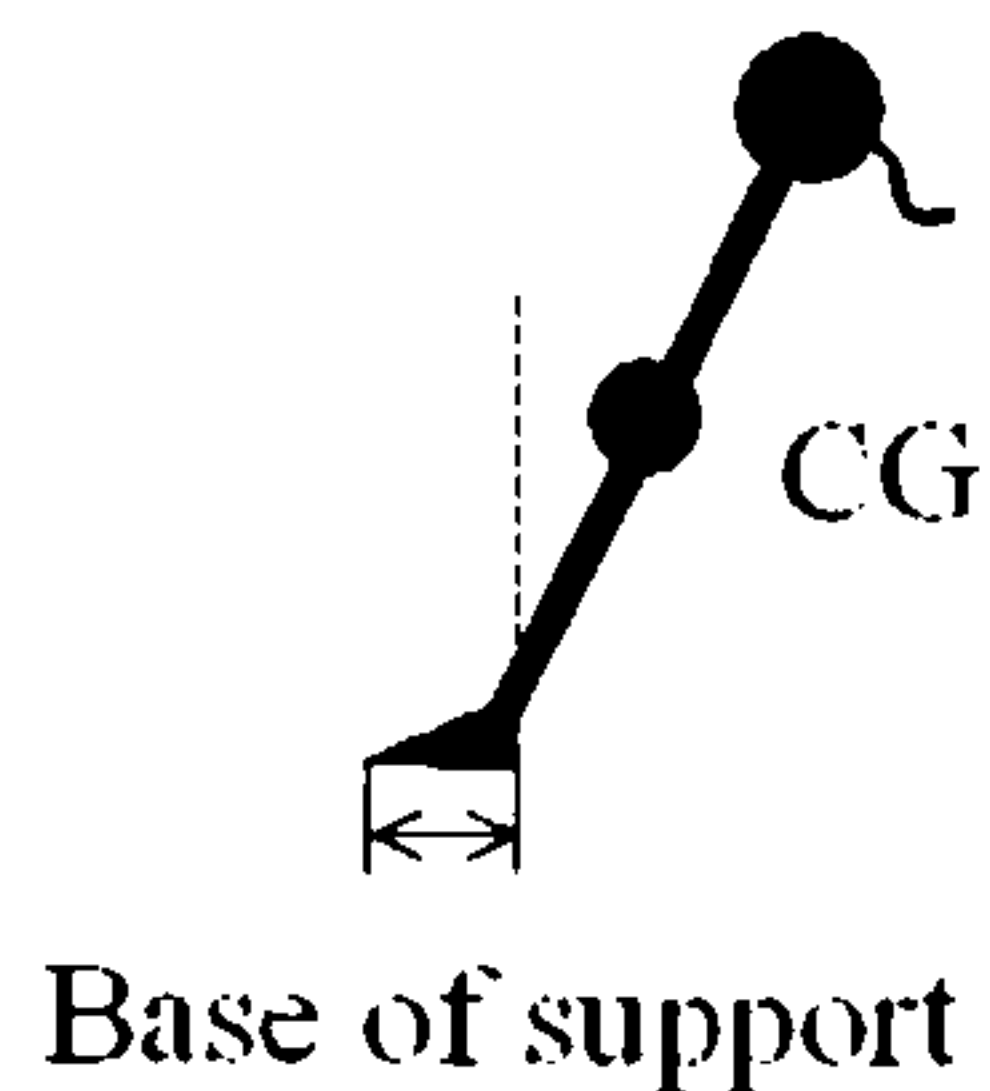


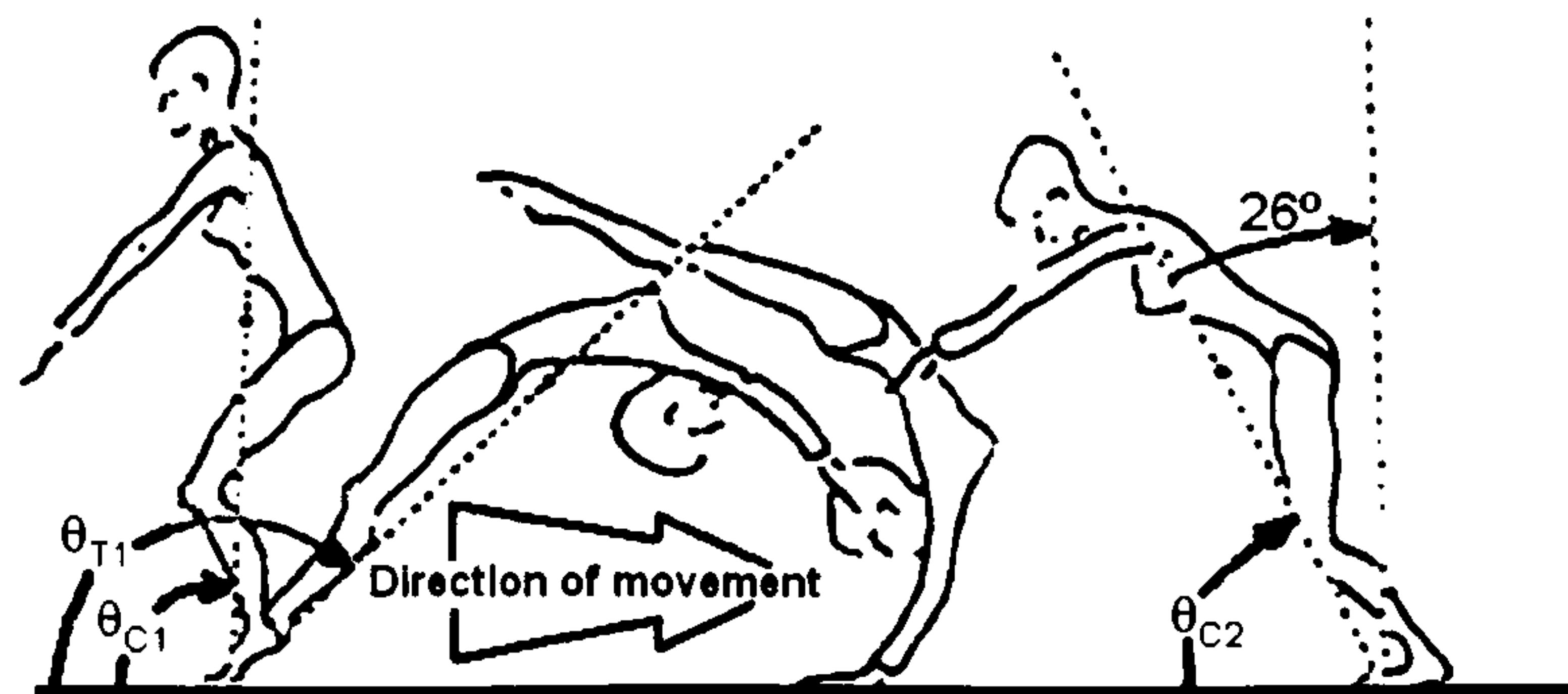
Figure 3-14: Falling Phase of the backward handspring.

In the dip phase the body moves from a straight position into a squat position with the hips and knees flexed, the ankles dorsiflexed, and the shoulders in full extension. Still (1990) explains that when the gymnast then executes the jump phase: jumping backwards into the first flight phase, while feet are still in contact with the ground, they exert a force forwards and downwards, and the ground reaction force is in the opposite direction: upwards and backwards. This propulsion phase involves a fairly rapid movement from the squat position to a position of whole body extension at takeoff. As the arms start to swing upwards opening the shoulder angle, the hip angle starts to open, closely followed by the start of knee extension and finally ankle plantar flexion (Nicol and Watkins, 1987). The push of the legs has both a horizontal and vertical component with which the gymnast increases the rotation and height of her CG, and is capable of diving back onto her hands.

The angular momentum of the gymnast should be sufficiently large to allow the body to pass through a handstand position, the body rotating about its axis to a standing position. When the hands reach the floor, the gymnast exerts a downward and backward force on the ground. Still (1990) observed that “the resultant reaction force was eccentric and therefore rotation occurred”. This resultant force adds to the existing rotation of the gymnast, assisting them into the standing position (Sands et al., 2003; Hay, 1993). During the phase between the feet touching the ground and the return of the body to a vertical position during the impact with the floor, some of the horizontal velocity of the CG is transferred into vertical velocity due to the body rotating about the feet, which aids the gymnast to stand (Liu et al., 2000).

In work carried out investigating velocities in backward handsprings, to determine how a gymnast prefers to approach a back somersault with regards to the velocity of approach, the theoretical backward handspring velocity ‘ v ’ (Figure 3.15) was calculated by means of the formula: $v = \omega r$, (Kriel, 1996), where ω was the backward handspring velocity, and r was the radius of the movement. The angular displacement of a complete

backward handspring was taken as 334° (360° minus 26°) because 26° was taken as the mean contact angle for the back somersault.



Where: θ_{T1} = contact angle, θ_{C1} = take-off angle, θ_{C2} = back somersault contact angle.

Figure 3-15: Angles and velocities of the backward handspring (adapted from Kriel, 1996).

Although this study accounts for the ‘falling’ phase of the backward handspring, as no forces are involved in the analysis it is not a complete description of the skill, and has only taken into consideration minimal factors which affect the complete dynamics of the skill.

Incorrect Technique and Resultant Problems

During the initial flight phase backwards, from feet to hands a common problem is lack of momentum and height. Hay (1993), explains that once off the ground, the gymnast should maintain the body in as straight a position as possible consistent with its angular momentum and the length of time it will be in the air. In this respect, a markedly arched back is generally regarded as an indication that takeoff was deficient and that as a result the gymnast is having to compensate (by decreasing the moment of inertia) to successfully complete the movement.

An example of a deficient takeoff is when the gymnast is not producing enough backwards force, which is a common problem with this skill. If the hips travel forward toward the toes at the beginning of the move (Figure 3.16a) rather than being pushed back behind the heels, the backward handspring will go upwards rather than backwards, and the gymnast will often end up ‘undercutting’ the move (Turoff, 1991). This will result in the gymnast placing the hands under the body rather than the hands contacting the floor well behind the initial position of the feet. To prevent this error from occurring, the driving push during the takeoff must come from the toes, not from the heels, but must be directed backwards through the whole foot. A lack of extension of the knees during this push backwards will also result in a non-maximal flight path (Warren, 2003). Gluck, (1982a) explains that a lack of extension of the hip angle and poor use of the arms will also result

in a lack of backward rotation, which can mean that the backward handspring will land short of the handstand position, and the gymnast will fall back towards the starting location of the skill, landing on the shoulders (Fig3.16b)

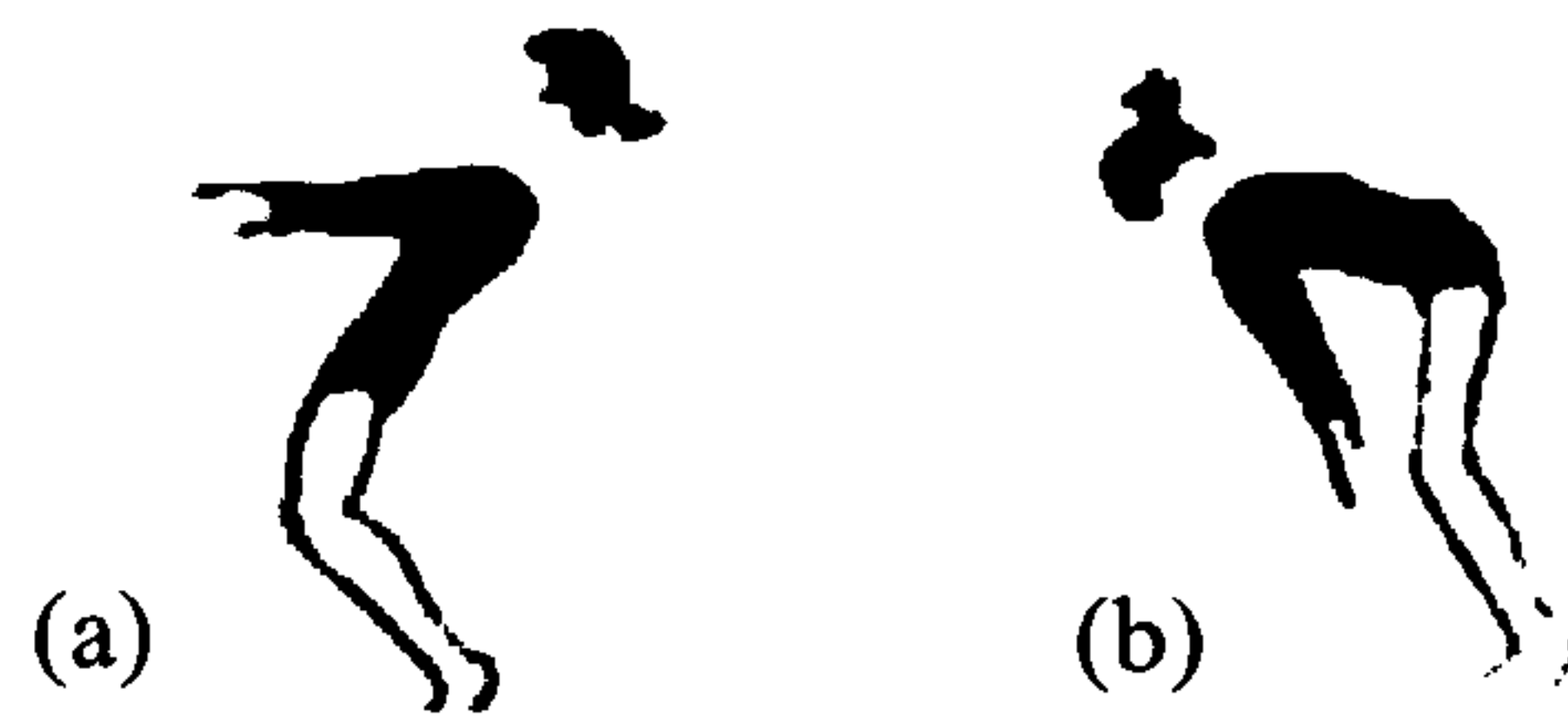


Figure 3-16: Poor techniques of the backward handspring: (a) Knees 'roll' forward (b) Lack of rotation on landing (adapted from Low, 1993).

During the second phase of the backward handspring, if the push from the arms while passing through the handstand position is insufficient, there are several unwanted resulting situations that may occur. Hay (1993) explains that if the body does not have sufficient angular momentum at this time, the gymnast will almost instinctively bend the arms and legs (decreasing the moment of inertia about an axis through the wrist) in an attempt to rotate safely over the hands and feet. Though this may be true, it is the linear velocity that will have the greatest effect on the success of a backward handspring. If there is not sufficient linear velocity then even a large angular velocity will not make the skill successful, but merely force the gymnast to close the angle and endangering head contact with the matting. Bending the arms excessively during a backward handspring will inevitably result with the gymnast landing on his or her head. If the horizontal velocity is sufficient, but the rotation is insufficient, then if the gymnast is strong enough to keep the arms straight, there is a high probability that the shoulder angle will close when the hands make contact with the floor. This can lead to the gymnast dropping the legs to the ground before the body has passed over the hands, and this will result in a failure of the skill from either a forward fall onto the hands from the feet, or even a collapse of the skill (Witten and Witten, 1983; Gluck, 1982a).

Existing Training Aids

Work carried out by Gervais et al. (2004), explains that an inclined mat is a common learning device used in the coaching of a backward handspring, and that it was found that the incline produced greater linear momentum in the direction of progression than an assisted backward handspring. The mat can be either specifically made for this purpose, or can be adapted from existing equipment, but an incline of around 13° is

generally used. Witten and Witten (1983), describe the use of a vaulting board as an incline rather than a mat (Figure 3.17) to aid the gymnast feel the loss of balance position more easily. The reason for the use of the incline is to encourage the gymnast to fall backward into the leg push, rather than simply jump upwards. This helps encourage the correct technique and direction to achieve a well-performed skill.



Figure 3-17: Vaulting board incline training device (adapted from Witten, 1983).

The rest of this section provides details on some of the existing training aids available in the market at present. The foam block below (Figure 3.18) is an example of a specifically manufactured incline. As mentioned previously, this training aid is to encourage the backward ‘dive’ action into the handstand position, but does not permit the gymnast to perform the skill unsupported. It is however available from the majority of gymnastics equipment manufacturing companies.

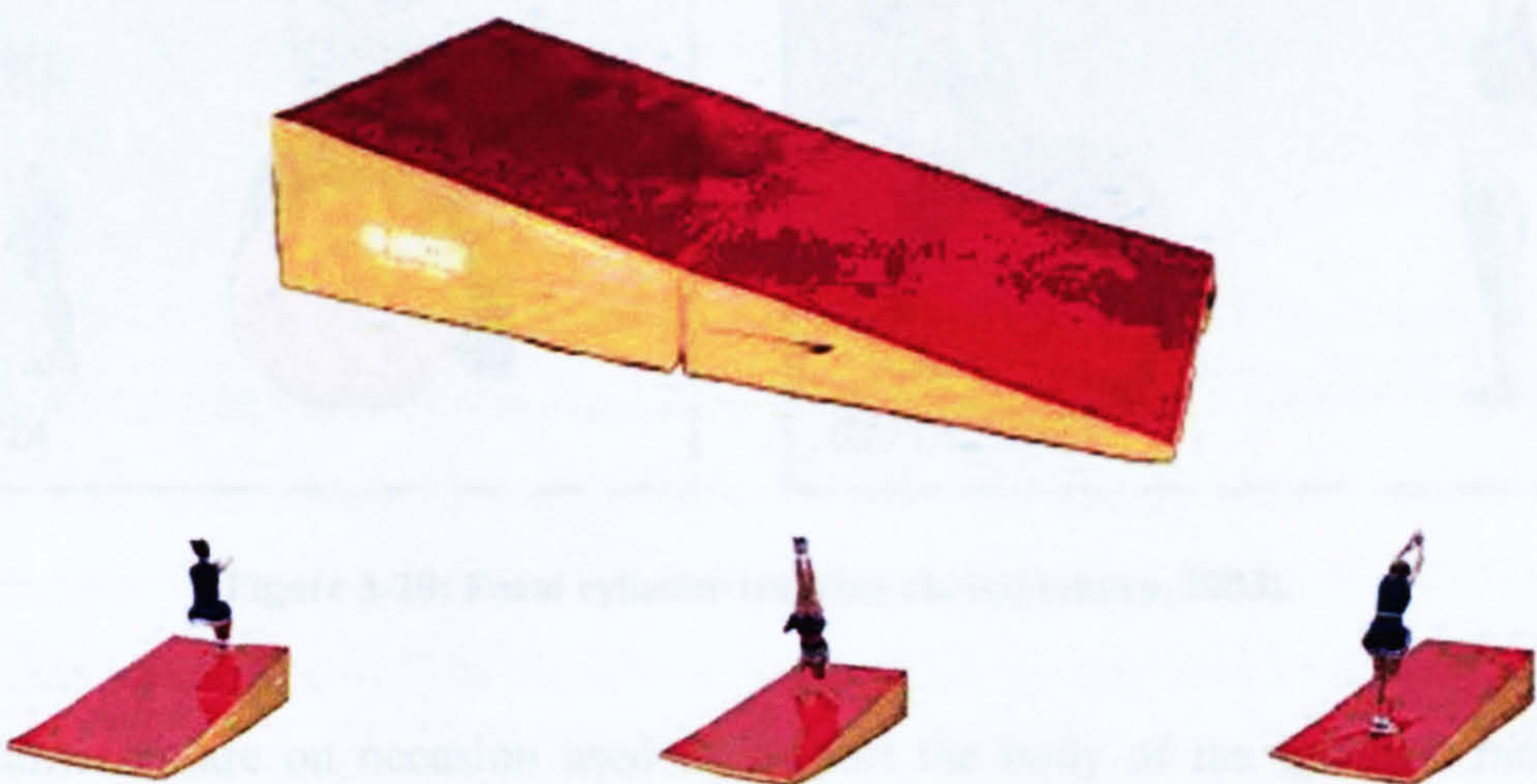


Figure 3-18: Foam incline training aid (adapted from United Athletic, 2003).

The second training aid is used to slowly position the gymnast through the first phase of the backward handspring (Figure 3.19), to increase the gymnast's awareness of the orientation of the skill, up to the point of passing through handstand. It is not deemed possible to perform a dynamic backward handspring using this training aid, and information obtained from the High Performance coaches' survey supported this decision.

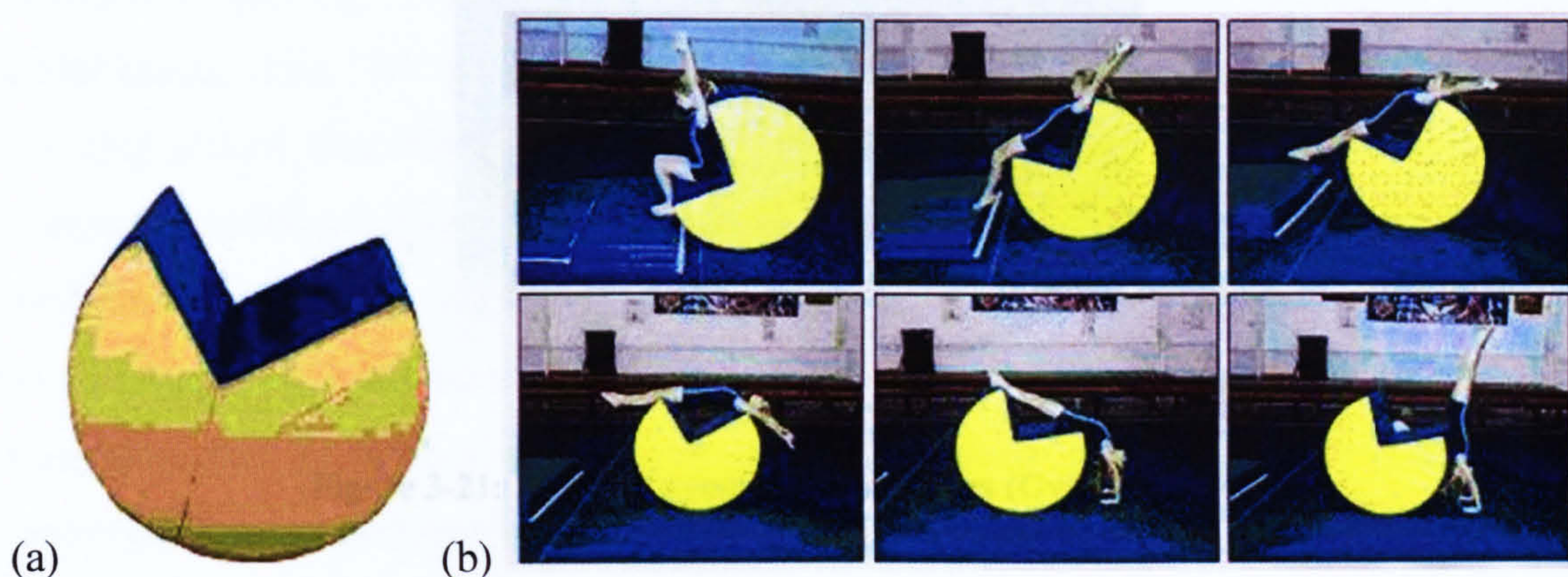


Figure 3-19: Foam $\frac{3}{4}$ cylinder training aid (a) United Athletic website, backward handspring trainer; (b) tracks2000.raonline.co.uk.

The foam cylinder manufactured by Gymnova (Figure 3.20) performs in a very similar manner to that of the three-quarter cylinder manufactured by United Athletic. However it provides less shaping awareness and does not provide the same quantity of support to the gymnast during the first phase of the skill.



Figure 3-20: Foam cylinder training aid (Gymnova, 2003).

Harnesses are on occasion used to support the body of the gymnast rather than manual coach support (Figure 3.21). This method is reliant upon the gymnast knowing how to perform the skill alone without shaping from the coach, and the training aid merely prevents the gymnast from landing on the head if the skill fails. A coach is also required to

use the harness, and so if manual shaping is still required, it would be necessary for two coaches to be involved in the supporting of the skill, one shaping and one operating the harness.



Figure 3-21: Assorted gymnastics harnesses (Gymnova, 2003).

Backward Handspring Summary

The training aid is to be designed to support a standing backward handspring, which is performed from a stationary start. The training aid will be required to help alleviate the anxiety involved in the performance of the skill, to make the skill safe to learn including supporting technically poor performances such as: undercutting, lack of backward movement, and bent arms on landing upside-down. The training aid needs to encourage the gymnast to begin the skill with a backward fall, but as the skill needs a forceful leg push at takeoff, soft matting cannot be used in this region of the training aid. Finally the training aid must permit a dynamic performance, whilst providing any required support, but should not interfere with a technically good performance. It will be necessary to identify differences in backward handsprings performed by different gymnasts to ensure that the training aid will be generally usable by all.

In terms of the design of the training aid, data must therefore be obtained in order to understand the magnitudes of movement involved in performing a backward handspring, the shape and dimensions of the parabola of the first flight phase, and how these parameters vary between gymnasts. A review of data obtained from previous studies on the backward handspring will be carried out to help identify how this data can be obtained, and if any other data should also be collected.

Data Collection

In a previous study (Nicol and Watkins, 1987) force plate data was collected on the takeoff for a backward handspring. The force data was then compared with film data of the performed skill. Forces and moments acting on each leg relative to the force plate reference origin were compared with the style and takeoff technique used to perform the backward handspring. This was in order to establish if similar takeoff techniques produced similar kinetic data. The video and force data were synchronised using a five LED device switching at 4ms intervals, and the subjects wore reflective markers on their joint centres for ease of motion analysis of the performed skill. The resultant muscle moment-time and power-time relationships were found in general to be similar for all subjects and for takeoff styles. Kriel (1996), as mentioned earlier, investigated the takeoff angles for the backward handspring, and for the backward somersault. The results discussed were obtained from video recordings of performances, from which angles were measured.

Studies carried out by Gervais et al. (2004), and Koh et al. (1992) also investigated the forces involved in backward handsprings. Gervais et al. (2004) investigated the peak ground reaction forces present during four different backward handspring techniques: a supported standing backward handspring, a standing backward handspring performed down an inclined mat, a backward handspring preceded by a round-off, and an accelerator backward handspring. Results showed that the ground reaction forces were significantly lower in the supported skill than in the other three skills performed. Koh et al. (1992) also compared technique with ground reaction forces with respect to injury prevention. It was found that the reaction force at the hand produced during the double-arm support phase were on average up to 2.37 times body weight.

Conclusion

As the data to be collected in this study is to enable the design of a training aid to support the backward handspring, it is important to understand the takeoff, flight, and landing characteristics of the skill. The shapes that the gymnast produces during the skill, and the '*free volume*' beneath the skill which would be available for the positioning of the training aid must all be established. From the literature reviewed it has been decided that video of the skill will be crucial in establishing the required information. From calibrated video, digitising can be used to provide such information as joint centre movement, skill length and height, and joint angles during the performance of the skill. This information will permit not only the design of a suitable training aid, but will also permit a comparison

between a skill supported by the training aid, and an unsupported performance of the skill by various gymnasts. This information can be used in the assessment of the training aid.

3.4 Summary of requirements for a generic training aid

The skill-specific requirements discussed previously in the literature review, along with technical, ergonomic and safety requirements for a generic gymnastics training aid have been compiled below and put into a design path for the creating of generic gymnastics training aids (Figure 3.22).

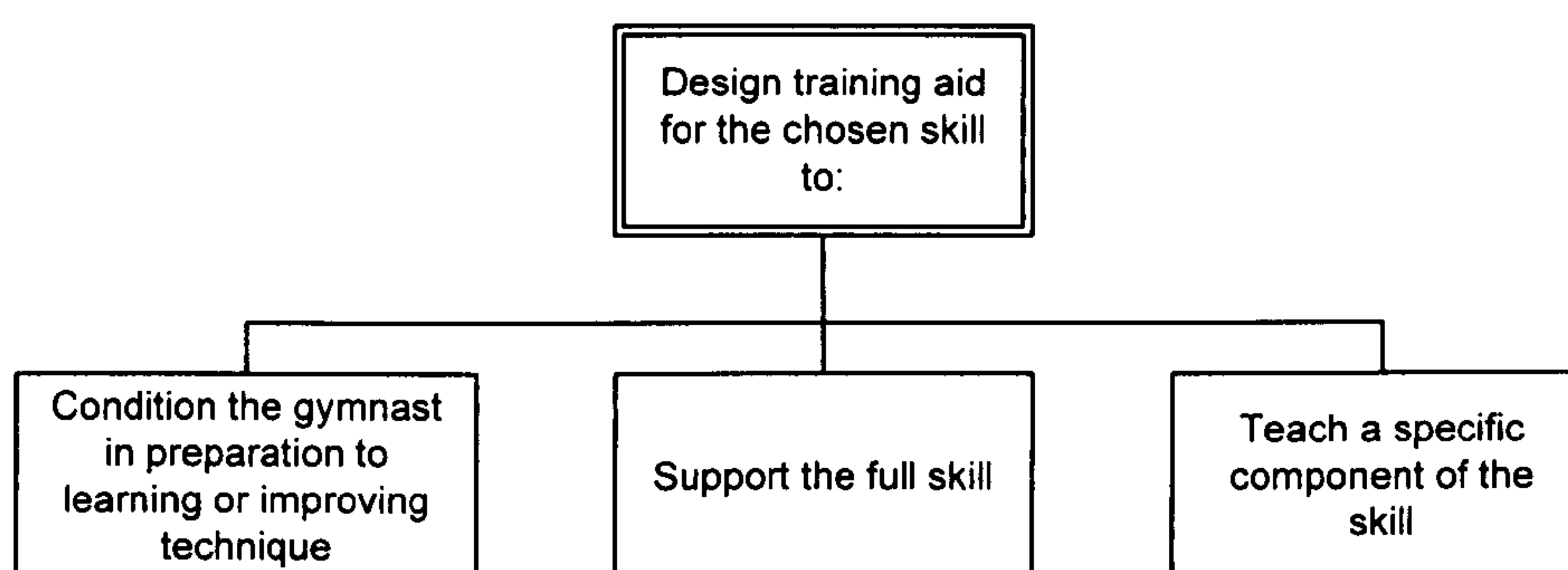


Figure 3-22: Top level of the design path for a gymnastics training aid.

The expanded design paths for the three possible types of gymnastics training aid are detailed below in Figure 3.23a, b and c. This complete design path has been developed in order to explain the process of designing a gymnastics training aid. The process described is specific to gymnastics but has been designed to encompass any gymnastics skill.

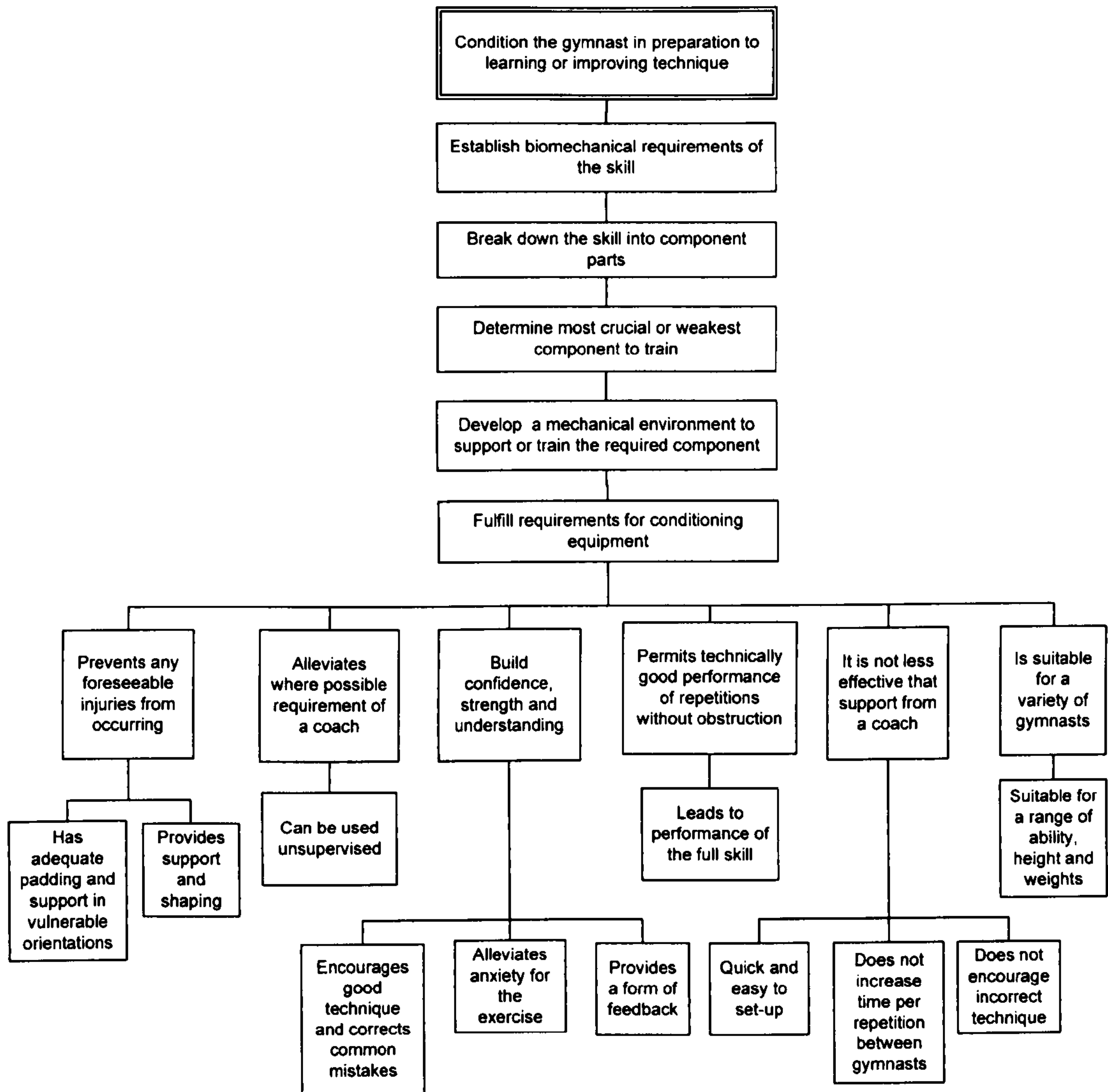


Figure 3-23: (a) Design path for the development of a conditioning training aid.

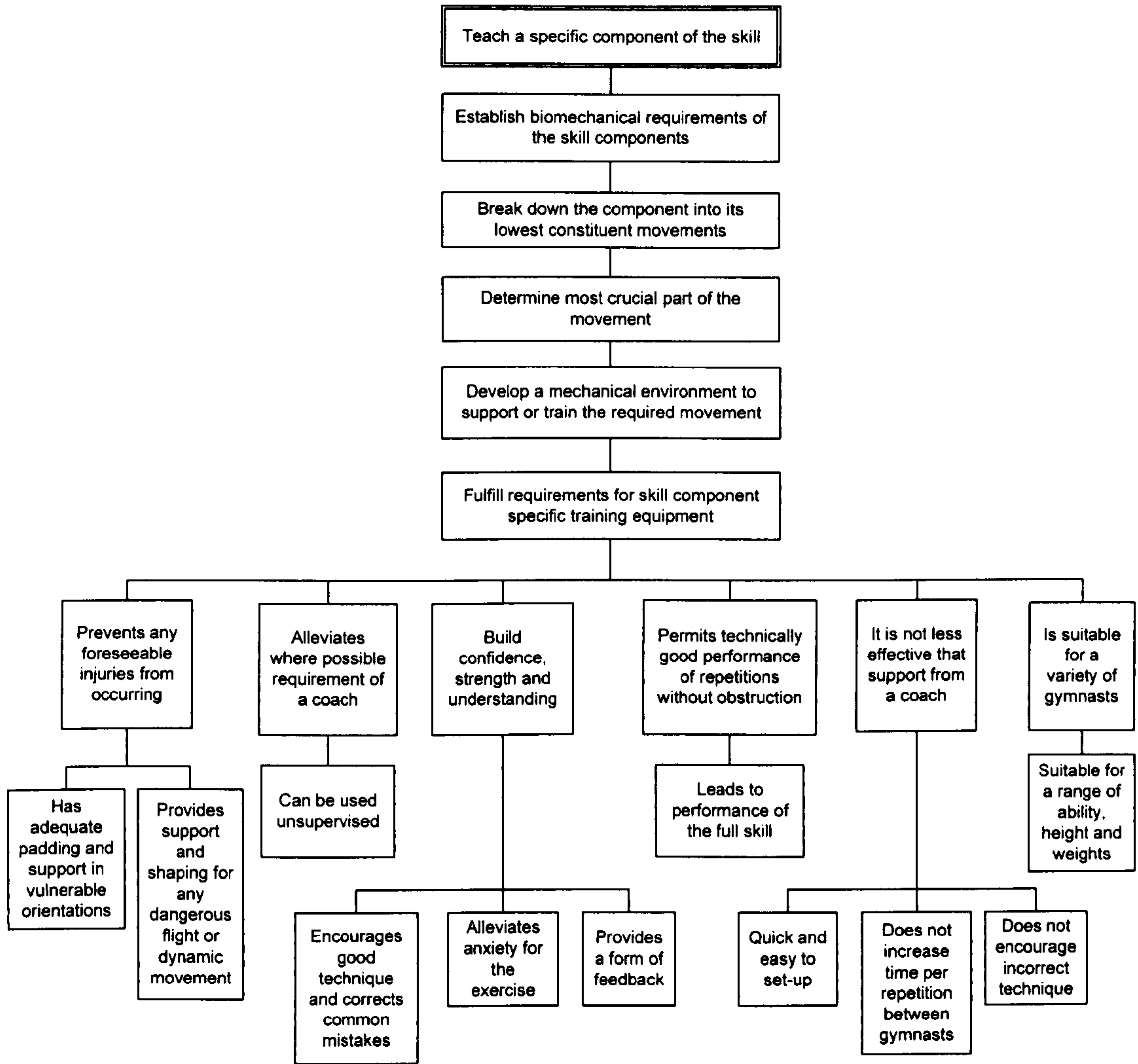


Figure 3-23: (b) Design path for the development of a training aid to teach a specific component of a skill.

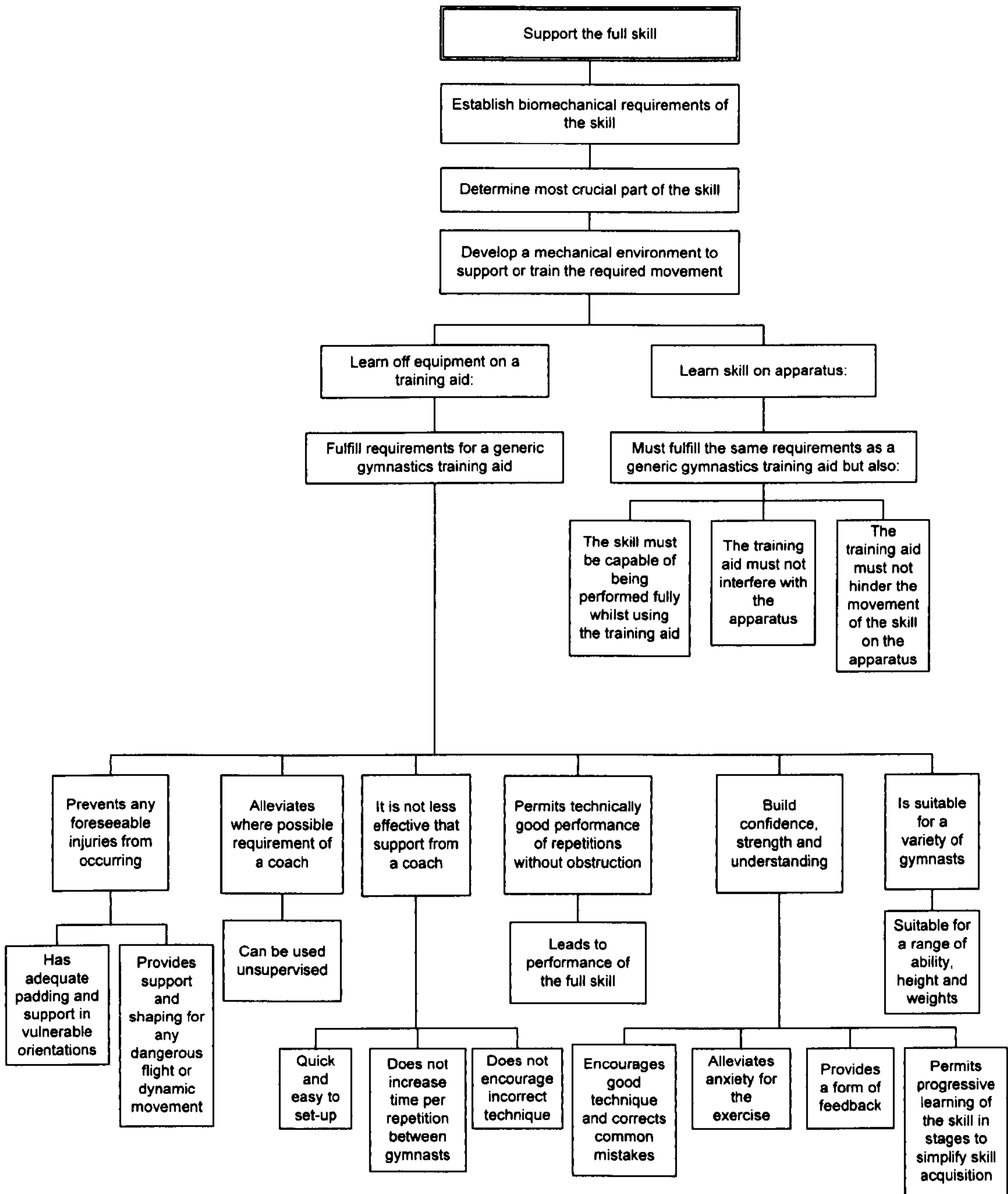


Figure 3-23: (c) Design path for the development of a training aid for a full skill.

3.4.1 Design methodology

From the design path, it is possible to diversify from gymnastics in order to produce a design methodology for the generic design of any training aid. This methodology can be applied to any sport or physical activity.

1. Choose the activity for which an aid is required, for example to assist an accident victim re-learn to walk.
2. Interview relevant persons for whom the aid will be designed, for example customers: injury victims, doctors, and physiotherapists. Establish the 'customer' requirements of the aid.
3. Analyse any existing aids for the chosen activity. Perform a competitor analysis, detailing the positive and negative elements of the existing aids with regards to the customer requirements. Identify if there is room for improvement, and what will produce this improvement.
4. Use the quality function deployment processes to ensure that the customer requirements are thoroughly considered during the design process.
5. Biomechanically analyse the chosen activity, and establish the different stages of the movement sequence, and determine which is most important.
6. Break down this stage into the most basic constituent movements, and determine the most important of these movements, e.g. for the motor control of walking.
7. Identify the requirements for making the chosen action safe but functional.
8. Design a mechanical or structural device which will replicate the real environment of the activity and make repetition safe and progressive, starting the activity at a basic level and increasing the difficulty as the 'customer's' capability develops. For example, walking at controlled slow speed on a treadmill whilst secured in a bungee harness in case of misplacing a foot.

This methodology is a more detailed version of the design process produced first in Section 3.1. Fulfilling some of the primary required tasks in the methodology above, will permit an efficient design of an effective training aid. First to be considered are the requirements of the customer for whom the training aids are being developed.

3.4.2 Customer requirements

To initiate the design process, it was first necessary to establish what were the perceived 'customer needs' of a training aid to help teach a handstand on the rings, and for

a training aid to help teach the backward handspring. During the interviews detailed in Section 3.1, a list of customer requirements was compiled from information provided by the coaches and senior gymnasts. The information has been analysed and collected together to produce two customer requirement trees (Figure 3.24 and 3.25). Both trees contain weightings to portray the priority of each requirement as determined by the customer interviews and questionnaire. As stated in the literature review in Chapter 2, requirement trees are an important component of the product design process (Figure 2.3).

Requirement Trees

Wright (1998) explains that the needs of the customers can be identified in terms of objectives and constraints, and that these needs can be organised into a requirement tree in order to help the designer explore the problem without looking for immediate solutions. A requirement tree can provide a means of ‘thought ordering’ for an individual designer working alone. It also allows the communication and record of developing views on the products requirements, but most crucially the requirement tree ensures that the designer is fully conversant with the needs of the customer.

Assigning weightings to objectives can be a method of avoiding problems between two conflicting requirements, for example between weight and durability. Wright (1998) explains that the weighting process is a method of specifying the importance of the requirements, whilst maximising customer satisfaction. The most common approach to weighting requirements is: the top-down approach. Wright (1998) explains that starting at the top of the tree, the top level is assigned a unitary weighting of 1. Proceeding down, each branch of the tree, each sub-objective is allocated portions of the unitary weighting, the summation of these portions equalling 1. Continuing down the branches, again the summation of the weightings of the sub-objectives must be 1. The overall weighting of the sub-objectives is calculated by consecutively multiplying the weighting values of two consecutive levels always starting at the top and working down. This value is often shown in brackets. For example if the second level of the requirement tree had weightings of: (a) 0.25 and (b) 0.75, and the third level had beneath requirement (a) had weightings of (c) 0.25 and (d) 0.75, then the actual values of the two requirements would be: (c) = $0.25 \times 0.25 = 0.0625$ and (d) = $0.25 \times 0.75 = 0.1875$.

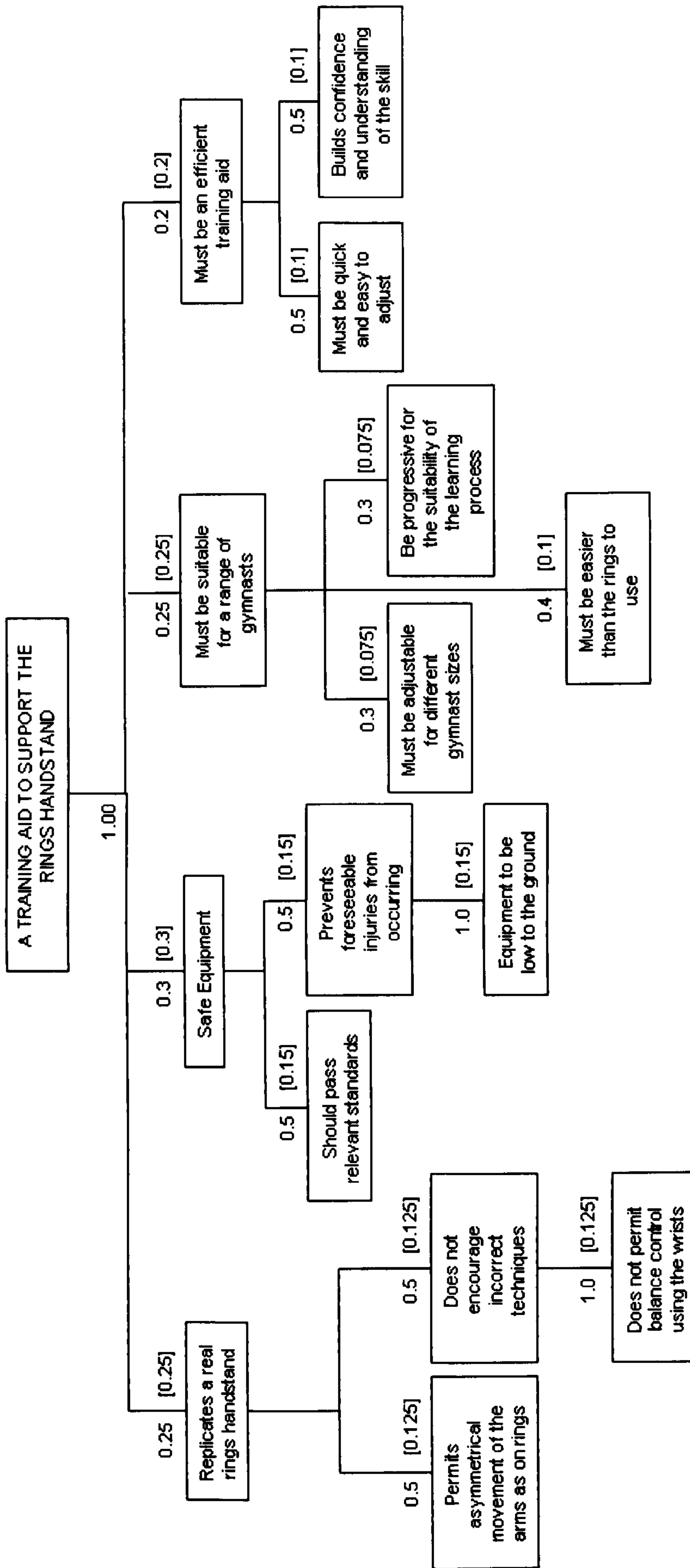


Figure 3-24: Customer requirement tree for the rings handstand training aid.

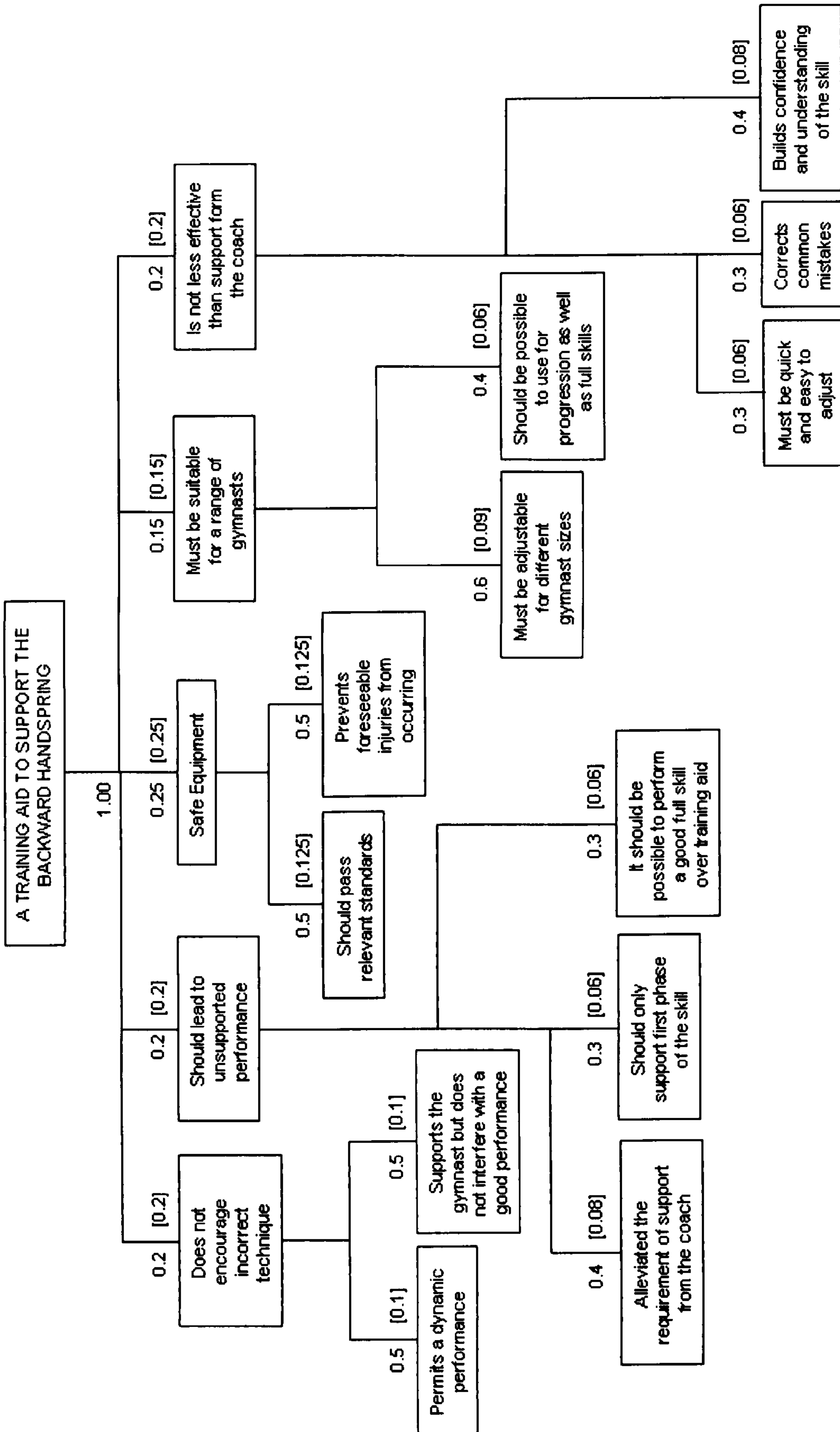


Figure 3-25: Customer requirement tree for the backward handspring training aid.

3.4.3 Customer analysis

It must be ensured that any training aid designed for either the handstand on the rings, or for the backward handspring must be more suitable than the existing training aids available. This can be achieved by comparing the 'competition' to a set of customer requirements, and hence highlighting flaws in the existing designs. Information from the customer interviews and from existing equipment assessments has been compiled and tabulated (Table 3.1 and 3.2) for ease of understanding. The bottom level requirements, alongside their respective weightings have been used to 'rate' the competitors against both the customer requirements and each other.

Table 3-1: Competitor analysis of existing rings handstand training aids

WEIGHTING	0.125	0.125	0.150	0.150	0.075	0.100	0.075	0.100	0.100	1.00
Product	Permit asymmetrical movements of the arms as on rings	Does not permit balance control using the wrist	Should pass relevant standards	Equipment to be low to the ground	Be adjustable for different sizes of gymnast	Must be easier than the rings to use	Be progressive for suitability of learning process	Quick and easy to adjust	Builds confidence and understanding of the skill	SCORE OUT OF 1.00
Handstand swing	x	x	✓	±	x	✓	x	—	±	0.38
Handstand bowl	x	x	✓	±	x	✓	x	—	±	0.38
Handstand mini bowls	✓	x	✓	✓	✓	✓	±	—	±	0.69
Mini rings	✓	✓	✓	±	✓	±	±	✓	✓	0.84

As can be seen from Table 3.1, the mini rings produced the best score. This was not surprising as they were the most similar to the rings. They do however still have their drawbacks, and these must be confronted and resolved during the design of the new rings handstand training aid.

Table 3-2: Competitor analysis of existing backward handspring training aids

WEIGHTING	0.100	0.100	0.080	0.060	0.060	0.125	0.125	0.090	0.060	0.060	0.060	0.080	1.00
Product	Permits a dynamic performance	Supports the gymnast but does not interfere with a good performance	Alleviates the requirement of support from the coach	Should only support the first phase of the skill	It should be possible to perform a good full skill over the training aid	Should pass relevant standards	Prevents foreseeable injuries from occurring	Must be adjustable for different size gymnasts	Should be possible to use for progression as well as full skills	Must be quick and easy to adjust	Corrects common mistakes	Builds confidence and understanding of the skill	SCORE OUT OF 1.00
Cylinder	x	x	x	✓	x	✓	±	x	✓	—	x	±	0.39
¾ cylinder	±	x	x	✓	x	✓	±	x	✓	—	x	±	0.44
Incline	✓	x	x	—	✓	✓	x	✓	±	—	±	±	0.48
Harness	✓	±	±	x	✓	✓	✓	✓	x	x	x	±	0.63

From the analysis of the products for the backward handspring, the harness produced the highest score. The main advantage of the harness were that it fully supported the gymnast, preventing foreseeable injuries from occurring. This was not surprisingly the most heavily weighted requirement from the survey, and this alone provided the harness with the highest score. There are however many downfalls of the harness as a training aid for the backward handspring as can be seen in Table 3.2. These factors must be addressed during the design of a new training aid to support the backward handspring.

3.4.4 Quality function deployment (QFD)

QFD provides a formalised method of linking customer requirements to the engineering factors within the project. By producing a ‘house of quality’ it becomes possible to establish which engineering factors effect which customer needs, and it also shows the ranking of the competitors for customer requirements (Figure 3.26 and 3.27).

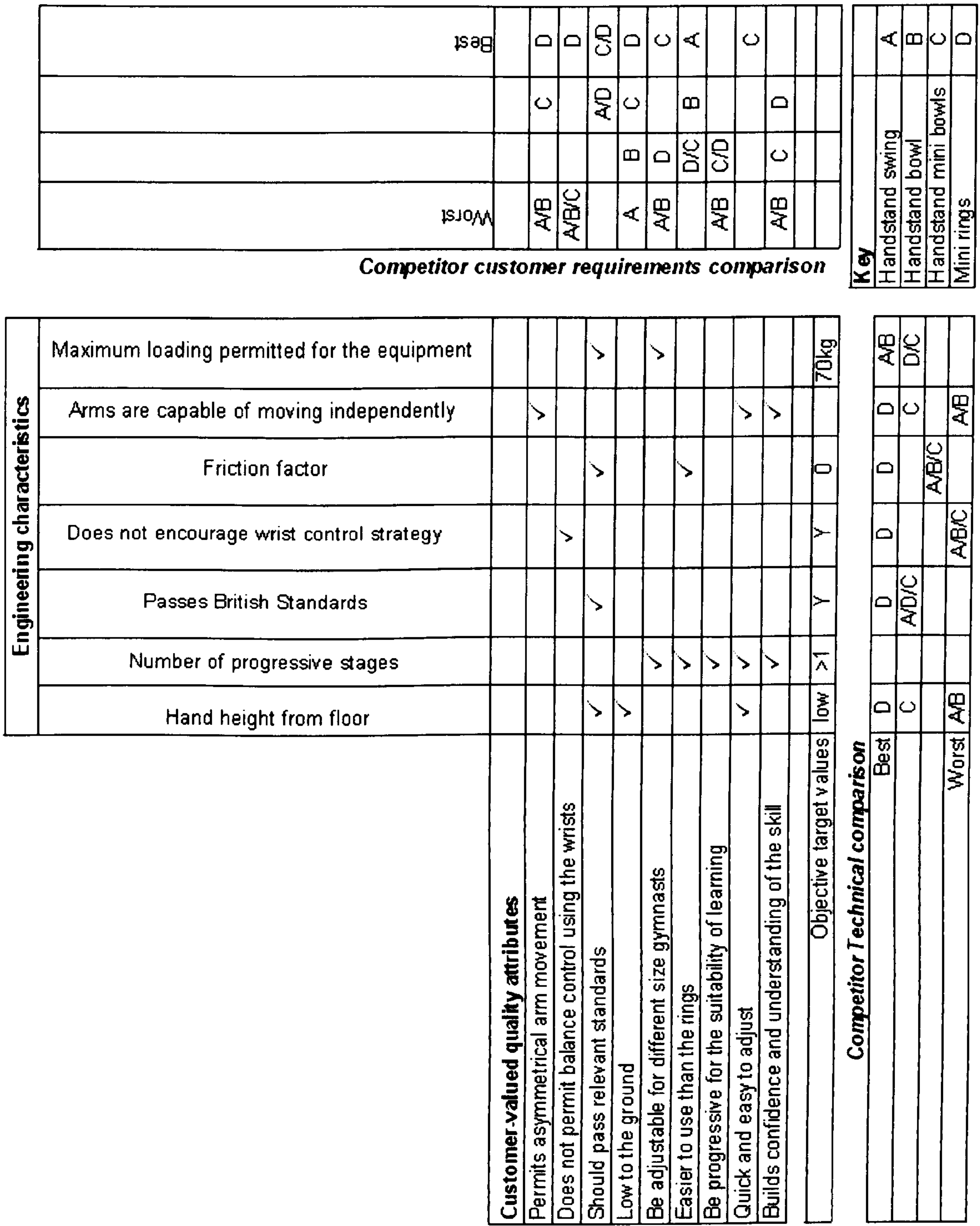


Figure 3-26: QFD-House of quality for the rings handstand training aid.

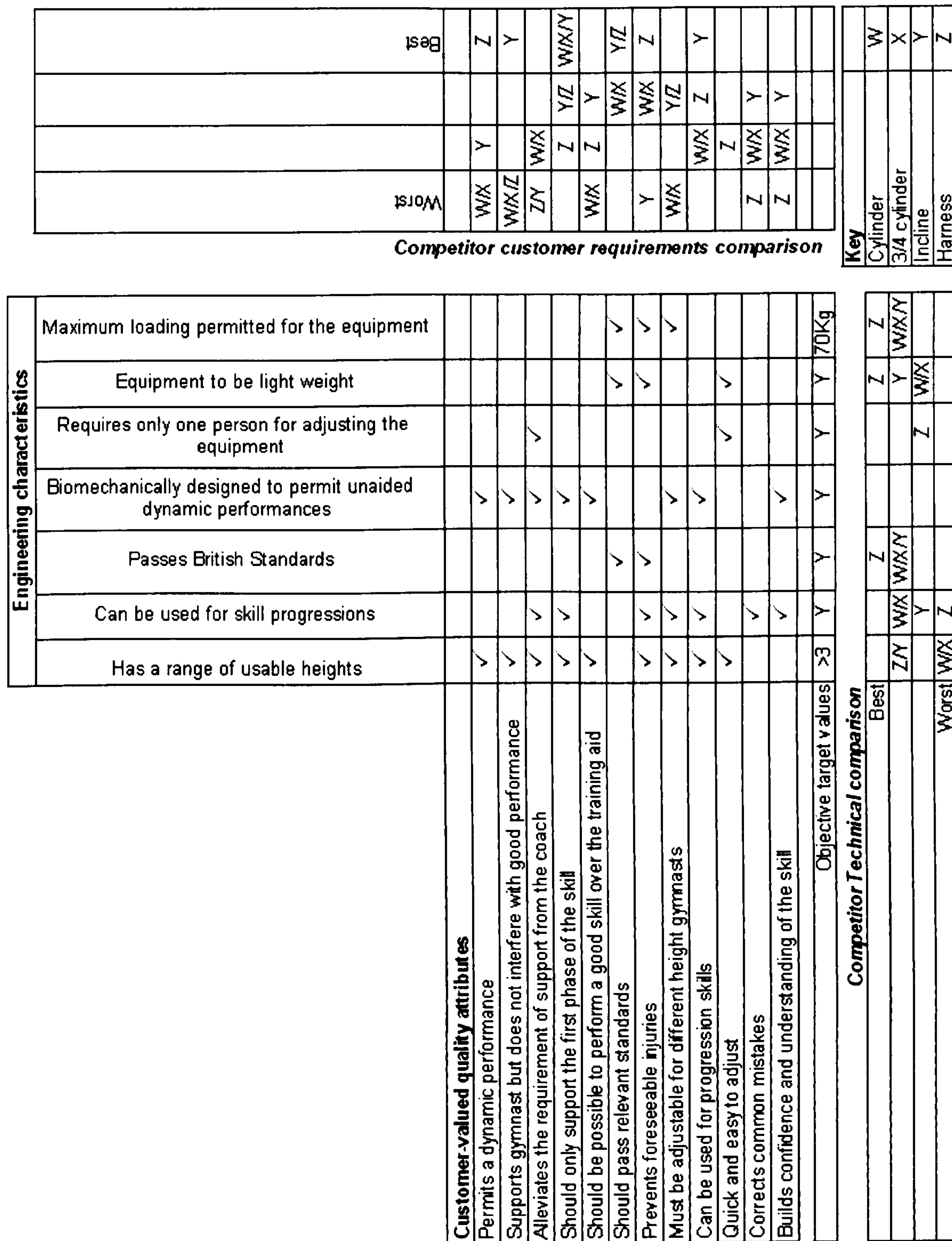


Figure 3-27: QFD-House of quality for the backward handspring training aid.

By using the QFD-house of quality in Figure 3.28 and Figure 3.29, it can be ensured that when considering the engineering factors involved in the design of the two gymnastics training aids, that none of the customer requirements will be compromised. The competitor analysis detailed in Tables 3.1 and 3.2 and in Figures 3.28 and 3.29 will also help ensure that the design of the new training aids will not incorporate the same flaws as the existing training aids, and will help assist in the success of the new designs.

3.5 Chapter summary

In this chapter, a methodology for the design of gymnastics training aids was developed, and this was then generalised in order to produce a generic methodology for any physical activity. The gymnastics specific methodology will be assessed in the following chapters through its use during the design and development of gymnastics specific training aids. The information discussed within this chapter, and the details concerning the requirements of the training aid designs will be used in the conceptualisation of the new equipment.

The main requirement of the rings handstand training aid is to provide a frictionless environment with sufficient space to permit the gymnast to balance the skill. The training aid should provide the six degrees of freedom discussed within this chapter, it should in no way require the recruitment of wrist control, and it should be suitable for gymnasts with a variety of shoulder widths.

The training aid for the backward handspring is in summary required to provide adequate support to the gymnast in order to prevent injury through poor technique, to help alleviate the anxiety involved during the performance of the skill, and to provide feedback to help the gymnast understand the shaping involved in the skill. It must be suitable for a range of gymnasts, and should not interfere with a skill performed correctly.

As can be seen from the design methodology in Section 3.1, the first four tasks have been completed, task five is to biomechanically analyse the chosen gymnastics skills, and this will be discussed in chapters 4 and 7. At this point in the thesis, the project will now separate into two separate design and testing sections. The first skill to be analysed will be the handstand on rings, and in the following chapter the initial data collection will be described.

4

Rings Handstand Analysis

4.1 Mechanical analysis of the handstand on rings

In order to conduct a full analysis of the handstand balance on rings, it is necessary to first understand the human control mechanism for maintaining balance in a handstand.

4.1.1 Introduction

Studies detailed previously (Chapter 3) have developed models of handstand on the floor, specifically Yeadon and Trewartha (2003) who developed a four segment model, and went on to investigate various control strategies. These strategies were dependent on torques being produced at the wrist, shoulder or hip in order to maintain the balance. The methodology of this thesis will be used to obtain the equations of motion and will then consider control strategies for the handstand on rings. There will be one significant difference between the control of a handstand on the floor and on the rings, as it was found that a handstand on the floor incorporates a torque at the wrist to maintain balance along with hip and shoulder torques to maintain body configuration.

In contrast, as discussed previously, when on the rings a gymnast cannot use a torque at the wrist to control the balance. This is because the hands have no rigid fixed surface upon which to create a reaction force to oppose motion. As the rings are suspended pendulums, when a horizontal force acts upon them, they simply move in the direction of the force. This does not permit the same method of balance control as can be utilised when performing a handstand on the floor. The gymnast therefore produces a torque at the shoulders to maintain balance. By doing this he moves his hands back under his mass centre, rather than re-positioning his mass centre back over his hands as he would for a handstand on the floor.

In order to simplify the analysis, a handstand on a moving frictionless surface (such as a skateboard for example) will be initially represented using a two segment

model, rather than incorporating a third segment to represent the rings cable. This will alleviate the complications of modelling the cable swing, as in a good quality handstand the swing should be minimal. It will also mean that all movement of the hands will be horizontal rather than along the circumference of a circle with a radius equal to the drop length of the hanging rings. As the length of the cable and ring combined is 3m, the curvature of the movement of the hands along this arc is only small, and therefore modelling this as a straight line is only a minor assumption. Even if the hands were to move $\pm 250\text{mm}$, this would only induce a rise of 10.4mm (Figure 4.1).

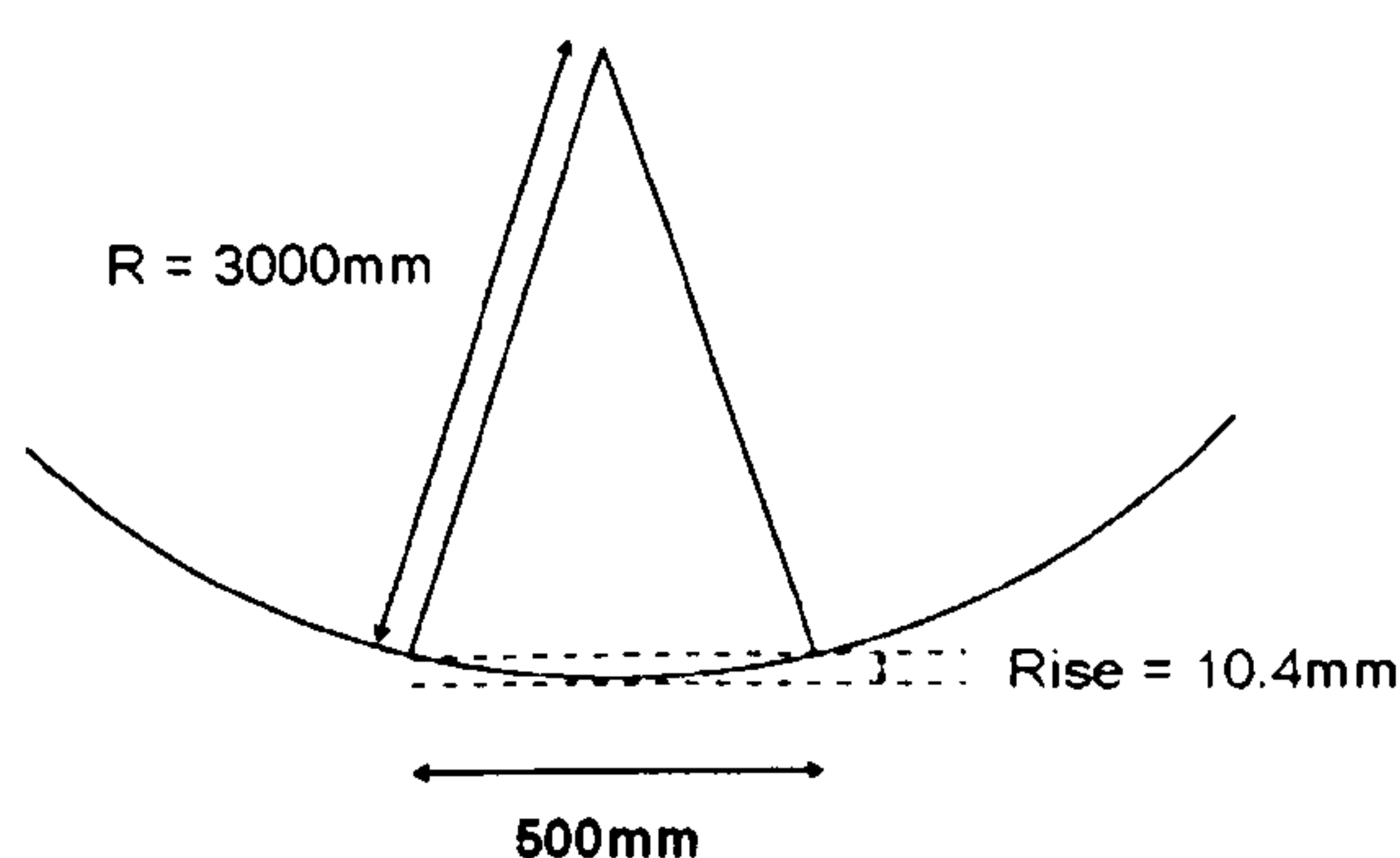


Figure 4-1: Curvature of rings motion explanation.

It will also be assumed in this model that the arms may only move forwards and backwards horizontally, unlike on the rings where the arms can also move sideways. In the reviewed literature and the coaches interviewed have stated that during the control of a handstand balance on the rings the main action used to maintain balance is through opening and closing the shoulder angle in the sagittal plane. If the arms move apart, along the frontal plane, this is normally associated with a significant loss of control, and unless the gymnast is of elite level, this movement will normally result in a fall from handstand. It is therefore feasible that this assumption be used during the modelling of this handstand.

4.1.2 Theory

It has been argued in the previous section that a handstand on the rings is controlled through variation of the shoulder angle, rather than the wrist angle as for a handstand on the floor. It is therefore possible to represent a handstand on the rings using a two segment model with a single joint. By producing a theoretical model of the handstand on the rings, it will be possible to demonstrate that balance may be

maintained using a suitable strategy for varying the shoulder torque as a function of the displacement and velocity of the system. The theoretical analysis will also be used to identify parameters characterising the balancing skill on rings in order to facilitate analysis of actual performances. The theoretical analysis will also be used to establish design parameters for an appropriate training aid.

The first segment, *A*, is the hands and arms, and the second segment, *B*, is the remainder of the body, the two segments being connected at the shoulder joint. It is assumed that there are no horizontal forces. This is shown in Figure 4.2 below.

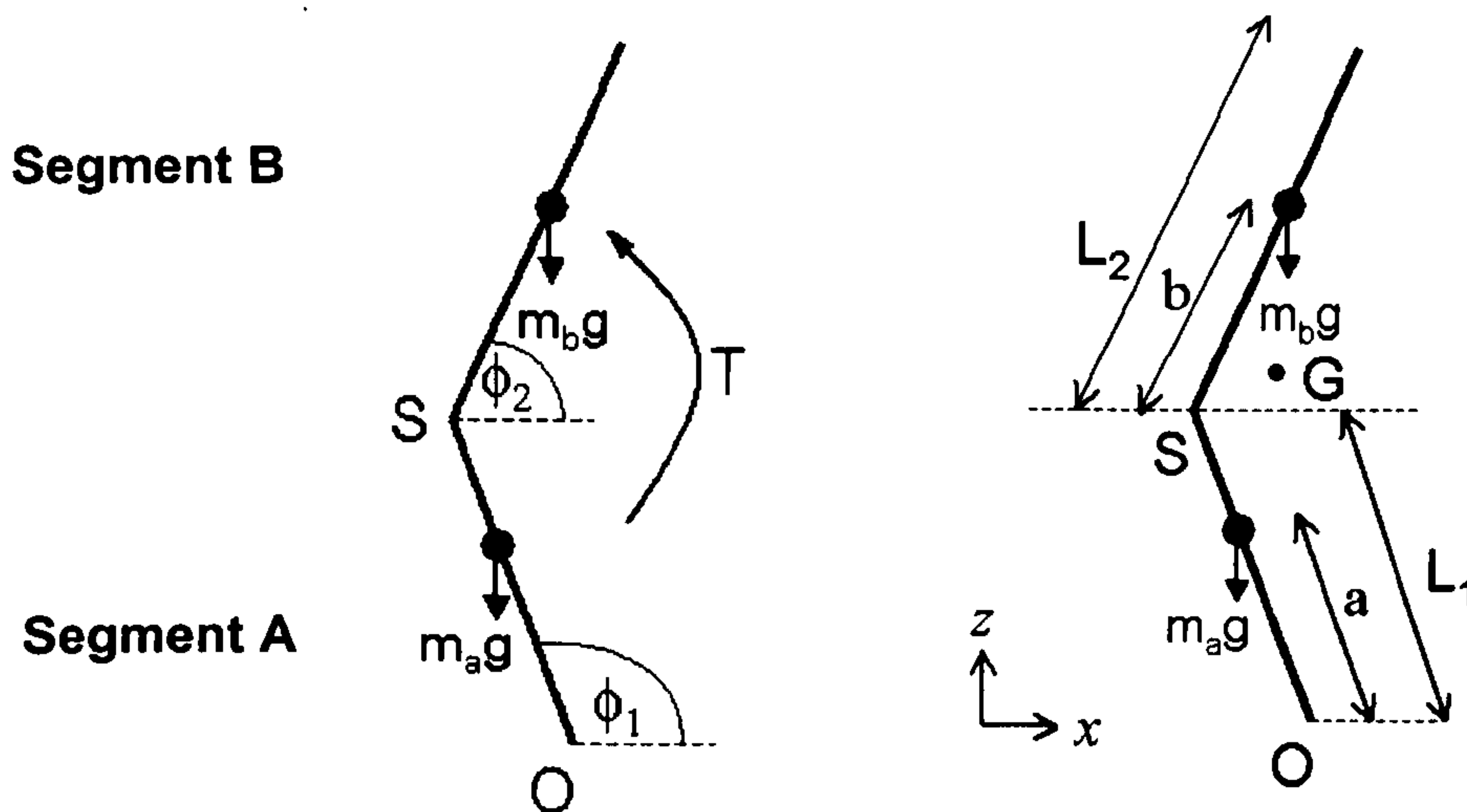


Figure 4-2: Model of the handstand on a surface free to move horizontally.

Shoulder Strategy

A torque T is applied at the shoulder joint S , in order to control the balance by ensuring that the whole body mass centre G is in close vertical alignment with the hands O . The method used to obtain the equations of motion for this system are similar to that of Yeadon and Trewartha (2003) which resulted in an equation of motion of the form $\ddot{X} = k^2 x - eT$ where T was the joint torque, X was the mass centre displacement and k and e were constants. For this system it was shown that stable control could be effected using control in the form $T = px + d\dot{x}$ providing the time delay was not too great. It is anticipated that a similar equation of motion will be obtained for the rings handstand using a shoulder torque to control the system. A full description of the mathematical model is detailed in Appendix D.

During a handstand a frictionless surface, as the mass centre does not move horizontally, $\dot{x}_G = \ddot{x}_G = 0$, and all measurements are made from a fixed location, so without loss of generality $x_G = 0$.

Taking moments about S for segment B gives:

Torque = rate of change of angular momentum

$$T - m_b g(x_b - x_s) = I_b \ddot{\phi}_2 - m_b \ddot{x}_b(z_b - z_s) + m_b \ddot{z}_b(x_b - x_s) \quad (1)$$

If T is then changed to $-T$ so that a positive torque corresponds to shoulder extension (closing the shoulder angle) Equation (1) becomes:

$$-T - m_b g b \cos \phi_2 = \frac{m_a m_b}{m} [bL_1 + ba] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} b^2 \right] \ddot{\phi}_2 \quad (2)$$

Taking moments about O for the whole system gives:

Torque = rate of change of angular momentum

$$\begin{aligned} -m_a g(x_a - x_o) - m_b g(x_b - x_o) = I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - m_a \ddot{x}_a(z_a - z_o) + m_a \ddot{z}_a(x_a - x_o) \\ - m_b \ddot{x}_b(z_b - z_o) + m_b \ddot{z}_b(x_b - x_o) \end{aligned} \quad (3)$$

where segments A and B have mass centres (x_a, z_a) and (x_b, z_b) , masses m_a , and m_b , and moments of inertia I_a and I_b about their respective mass centres.

Assuming that ϕ_1 and ϕ_2 remain close to $\pi/2$, throughout the balance, the motion of the mass centres a and b will be primarily horizontal so that \ddot{z}_a and \ddot{z}_b may be neglected and $\sin \phi_1$ and $\sin \phi_2$ may be approximated as 1.

Equation (3) becomes:

$$\begin{aligned} -mg(x_g - x_o) = I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - \frac{m_a m_b}{m} a [L_1 \ddot{\phi}_1 + b \ddot{\phi}_2 - a \ddot{\phi}_1] + \frac{m_a m_b}{m} [L_1 + b] [L_1 \ddot{\phi}_1 + b \ddot{\phi}_2 + a \ddot{\phi}_1] \\ = \left[I_a + \frac{m_a m_b}{m} [(L_1 + b)(L_1 + a) - aL_1 + a^2] \right] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} [(L_1 + b)b - ab] \right] \ddot{\phi}_2 \\ = \left[I_a + \frac{m_a m_b}{m} [L_1^2 + bL_1 + ab + a^2] \right] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} [L_1 b + b^2 - ab] \right] \ddot{\phi}_2 \end{aligned} \quad (4)$$

Multiplying Equation (4) by some constant $-\lambda$ to be determined, and then subtracting Equation (2) gives:

$$\begin{aligned} T + \lambda mg \left[(x_g - x_o) + \frac{m_b}{\lambda m} x_1 \right] = -\ddot{\phi}_1 \left[\beta(bL_1 + ba) + \lambda \left(I_a + \beta(L_1^2 + bL_1 + ab + a^2) \right) \right] \\ - \ddot{\phi}_2 \left[(I_b + \beta b^2) + \lambda (I_b + \beta(L_1 b + b^2 - ab)) \right] \end{aligned} \quad (5)$$

Where $\frac{m_a m_b}{m} = \beta$, $x_1 = b \cos \phi_2 = x_b - x_s$, and $X = (x_g - x_o) + \frac{m_b}{\lambda m} x_1$.

Double differentiating equation X and multiplying by m gives:

$$\begin{aligned}
 m\ddot{X} &= -m_a a \ddot{\phi}_1 - m_b (L_1 \ddot{\phi}_1 + b \ddot{\phi}_2) - \frac{m_b}{\lambda} b \ddot{\phi}_2 \\
 m\ddot{X} &= (-m_a a \ddot{\phi}_1 - m_b L_1 \ddot{\phi}_1) - m_b b \ddot{\phi}_2 - \frac{m_b}{\lambda} b \ddot{\phi}_2 \\
 m\ddot{X} &= -(m_a a - m_b L_1) \ddot{\phi}_1 - m_b b \left[1 + \frac{1}{\lambda} \right] \ddot{\phi}_2
 \end{aligned} \tag{6}$$

To eliminate $\ddot{\phi}$ from the Equation (5), if λ is chosen so that coefficients of $\ddot{\phi}_1$ and $\ddot{\phi}_2$ in Equation (5) are each some constant ψ times the corresponding coefficient in Equation (6), then Equation (5) may be written as:

$$T + mg\lambda X = \psi m \ddot{X} \tag{7}$$

Or equivalently:

$$\ddot{X} = k^2 X - eT, \text{ where a suitable choice of } T \text{ should be given.} \tag{8}$$

$$\text{where } k^2 = \frac{g\lambda}{\psi} \text{ and } e = \frac{1}{\psi m}, \text{ and where } \lambda \text{ is given by: } \frac{\lambda A + B}{\lambda C + D} = \frac{E}{\left(\frac{\lambda + 1}{\lambda}\right) F} \tag{9}$$

Control Strategy

Following the procedure of Yeadon and Trewartha (2003), from (8) the displacement X of the system is governed by the equation:

$$\ddot{X}_1(t) = k^2 X_1(t) - eT_1(t), \text{ where } t \text{ is the time.} \tag{10}$$

If T is based on the displacement X_1 and a velocity \dot{X}_1 at an earlier time, then the torques becomes:

$$T(t) = pX_1(t - t_0) + d\dot{X}_1(t - t_0) \tag{11}$$

which is an example of a closed loop PD control system.

If each coefficient is positive in a damped simple harmonic motion equation, then stable control will have been achieved.

By analysing the coefficients, and rearranging them to produce limiting equations, the conditions for achieving positive coefficients leads to:

$$\frac{k^2}{e} < p < \frac{2}{et_0^2} \quad (12)$$

$$\frac{k^2 t_0}{e} < d < \frac{2}{et_0} \quad (13)$$

and by combining the two equations above with the initial limiting equations:

$$\frac{1}{2kt_0} < \frac{p}{dk} < \frac{1}{kt_0} \quad (14)$$

Providing that the value of t_0 is not too large, there will a range of values for p and d which will satisfy the three limiting conditions described above in equations (12), (13), and (14).

If Equation (14) is balanced to give a limiting value for p/d then:

$$\frac{1}{2}k^2 t_0 = \frac{1}{t_0}, \text{ rearranging gives:}$$

$$t_0^2 = \frac{2}{k^2}, \text{ square rooting both sides of the equation gives the limiting value of } t_0:$$

$$t_0 = \frac{\sqrt{2}}{k} \quad (15)$$

Therefore inverting and substituting Equation (15) back into Equation (14) gives:

$$\frac{p}{d} = \frac{k}{\sqrt{2}} \quad (14)$$

For a given value of t_0 , the range of values of p/dk which correspond to stable control for this time delay can be seen in Figure 4.3 below.

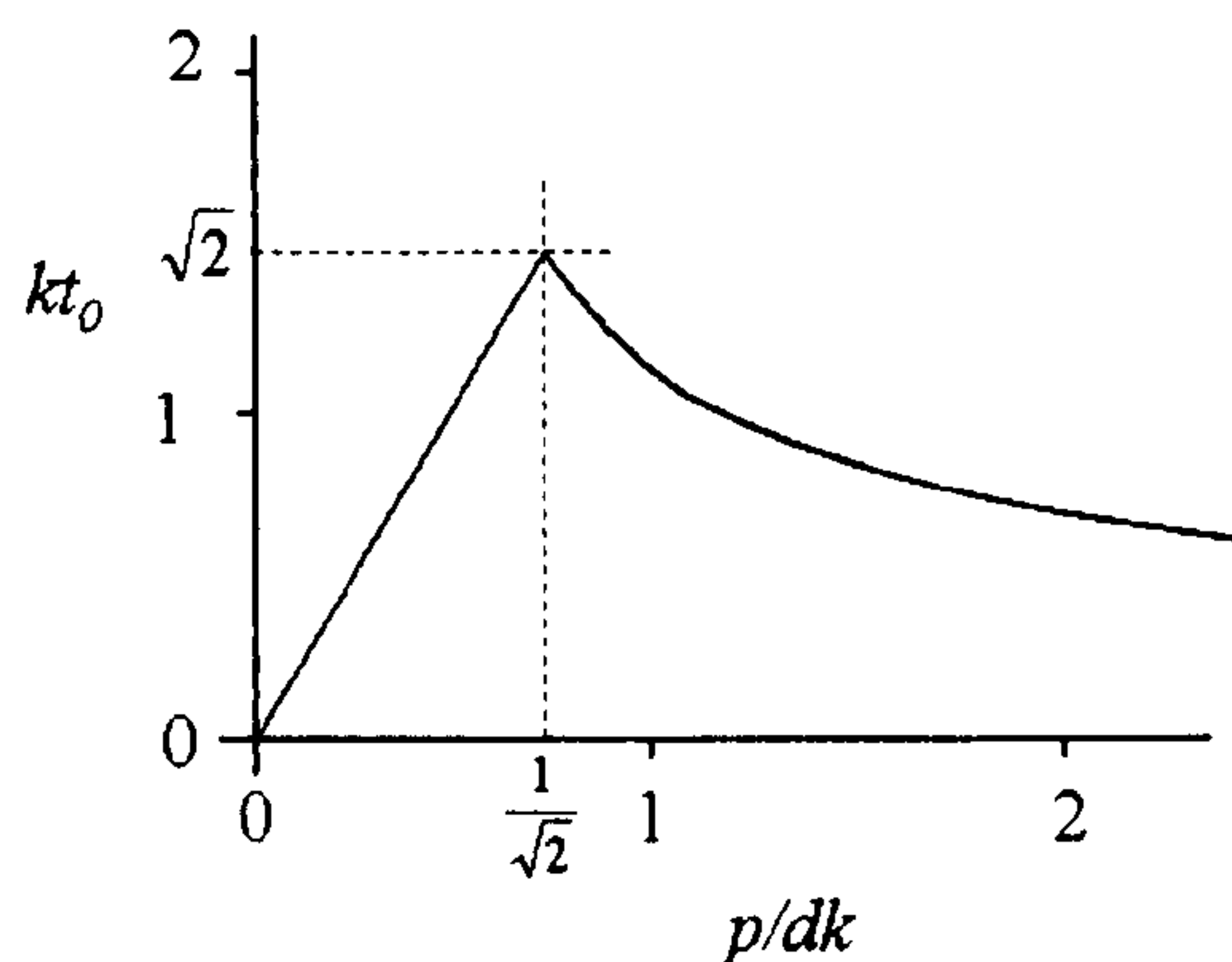


Figure 4-3: The region under the curve gives values of p/dk which correspond to stable control (adapted from Yeadon and Trewartha, 2003).

Substituting into Equation (12):

$$\frac{k^2 t_0}{e} = d \text{ then, } d = \frac{\sqrt{2}k}{e}$$

Summarising the work above:

The limiting value of t_0 is $\sqrt{2}/k$, with the corresponding values of $p = k^2/e$, and

$$d = \sqrt{2}k/e$$

This approximate solution for the control mechanism of a handstand on the rings been compiled from the same limiting mathematical equations as the wrist control strategy in Yeadon and Trewartha (2003), however they are mechanically different situations. The control strategy discussed here is not for the wrist, it is for the shoulder. This means that when making the assumption that T is based on the displacement X_1 and a velocity \dot{X}_1 at an earlier time t_0 , then the parameter T is shoulder torque, rather than wrist torque as in the Yeadon and Trewartha model. Similarly, when considering X , in this model this is the distance from the wrist to mass centre plus a proportion of the distance from the shoulder to the mass centre of segment B (the torso, and legs), in the Yeadon and Trewartha model, x_0 is fixed to the floor and so this parameter only describes the movement of the wrists.

Although this model has been written for an induced torque at the shoulder, it could similarly be for a torque at the hip, depending on the motion performed on the rings. It is expected however that the control motion will be from the shoulder as the reviewed coaching literature suggests.

Calculating the Value of λ

Using the anthropometric data collected from and elite male Artistic gymnast S, the individual body segment masses, positions of mass centres, lengths, and inertia parameters were calculated using the Yeadon inertia model (Yeadon, 1990). Using these parameters (Table 4.1) it was possible to systematically calculate the moment of inertia, and the position of the mass centre of combined segments:

Table 4-1: Data derived from Yeadon's (1990) inertia model, for gymnast S

Segment	Segment mass (kg)	Lateral Moment of inertia	Distance of mass centre from parent joint (m)	Segment length (m)
Head	5.43	0.03	0.13	0.26
Trunk	33.48	1.18	0.32	0.62
Arm -L	4.84	0.18	0.26	0.73
Arm -R	4.84	0.18	0.25	0.73
Leg -L	14.71	1.12	0.36	1.06
Leg- R	14.91	1.14	0.36	1.05

Combining the trunk and head segment

The distances from the mass centres to the shoulder joint were calculated using the segment length and the distance of the segment mass centre to the parent joint (Figure 4.4).

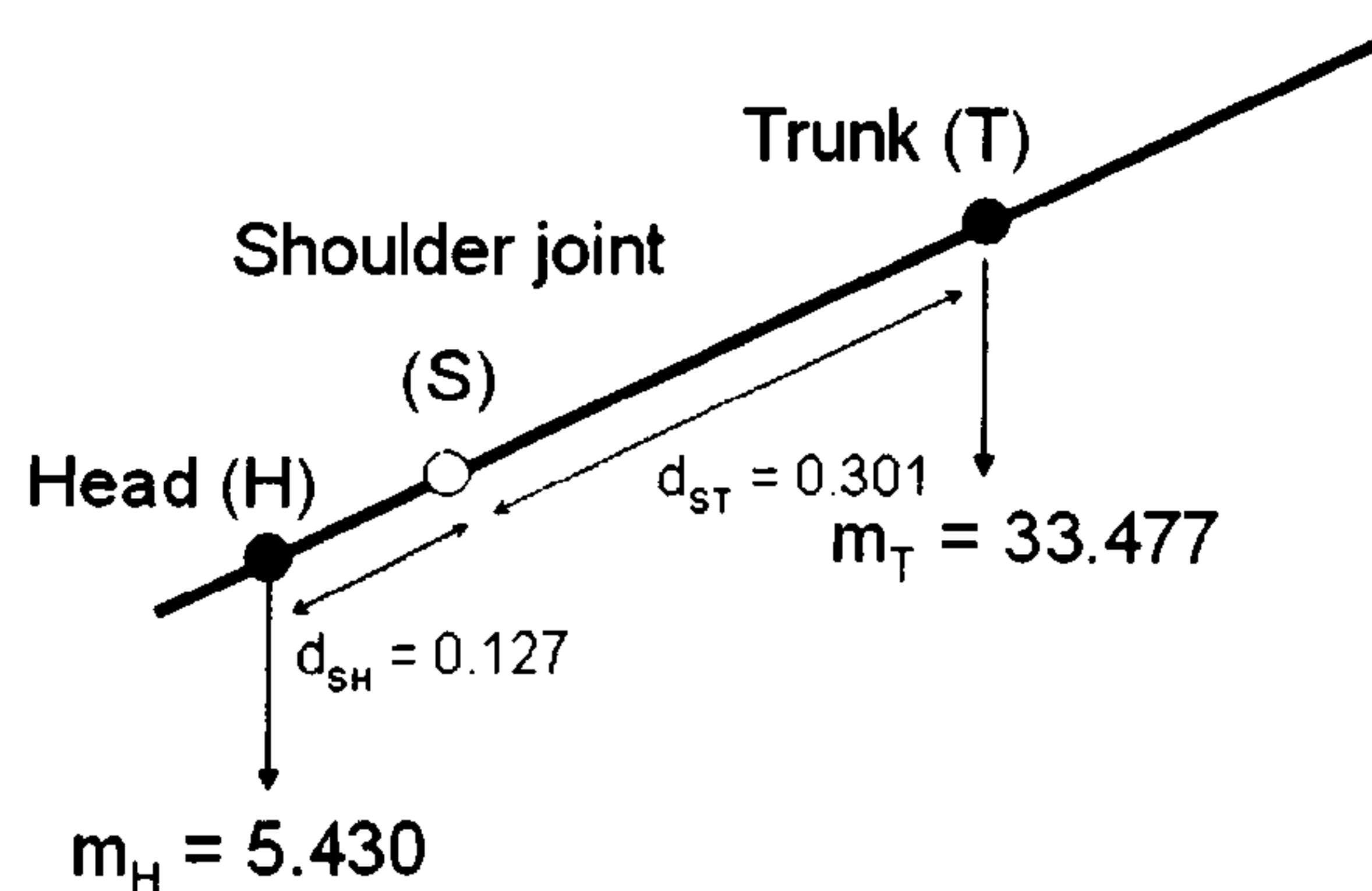


Figure 4-4: Schematic of the upper body segment of the gymnast.

Calculating moments clockwise about S:

$$\sum M = (33.477 \times 0.301) - (5.430 \times 0.127) = 9.387 \text{ kg.m}$$

Calculating the equivalent mass centre of the new segment Upper Body (UB):

$$m_{UB} = 5.430 + 33.477 = 38.907 \text{ kg}$$

The distance to the equivalent mass centre (d_{UBS}) = $9.387 \div 38.907 = 0.241 \text{ m}$, from S towards the hip.

where:

$$\text{The distance from H to } m_{UB} (d_H) = d_{SH} - d_{UBS} = 0.386 \text{ m}$$

$$\text{The distance from T to } m_{UB} (d_T) = d_{ST} - d_{UBS} = 0.060 \text{ m}$$

Using the parallel axis theorem about the lateral axis:

$$I_{UB} = (I_H + m_H d_H^2) + (I_T + m_T d_T^2) = 2.071 \text{ kg.m}^2$$

For shoulder control the segment UB must now be added to the legs in using the same method as above:

Combining segment UB with the leg segment

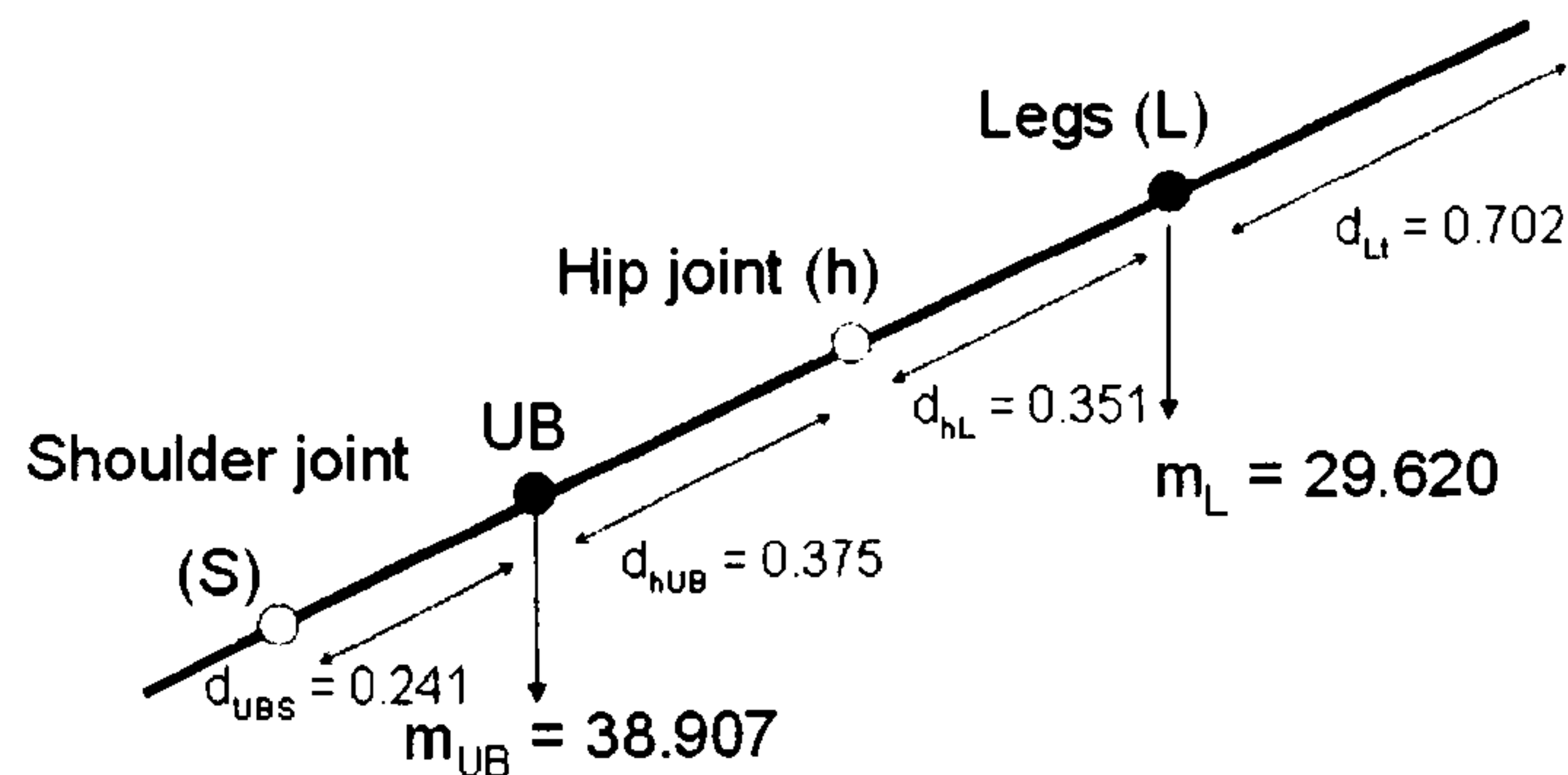


Figure 4-5: Schematic of segment B of the 2 segment handstand model.

Calculating moments clockwise about S :

$$\sum M = (38.907 \times 0.241) + (29.620 \times (0.241 + 0.375 + 0.351)) = 38.030 \text{ kg.m}$$

Calculating the equivalent mass centre of the new segment B (Figure 4.2 and 4.5):

$$m_b = 38.907 + 29.620 = 68.527 \text{ kg}$$

The distance to the equivalent mass centre (d_b) = $68.527 \div 38.030 = 0.555 \text{ m}$, from the S towards the hip.

Where:

$$\text{The distance from } UB \text{ to } m_b (d_{UB}) = d_b - d_{UBS} = 0.314 \text{ m}$$

$$\text{The distance from } L \text{ to } m_{UB} (d_L) = d_{UBS} + d_{hUB} + d_{hL} - d_b = 0.412 \text{ m}$$

Using the parallel axis theorem about the frontal axis:

$$I_b = (I_{UB} + m_{UB} d_{UB}^2) + (I_L + m_L d_L^2) = 13.187 \text{ kg.m}^2$$

Calculating the parameters in Equation (9):

$$A = I_a + \beta(L_1^2 + bL_1 + ab) + a^2 = 10.787$$

$$B = \beta(bL_1 + ba) = 5.679$$

$$C = I_b + \beta(L_1^2 b + b^2 - ab) = 16.999$$

$$D = I_b + \phi b^2 = 15.799$$

$$E = m_a a + m_b L_1 = 54.699$$

$$F = m_a b = 5.369$$

where $\beta = \frac{m_a m_b}{m} = 8.478 \text{ kg}$, and m_a is the mass of the two arms, and m_b is the mass of segment B .

Using the quadratic function to now solve Equation (9)

$$\lambda = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}, \text{ where } \lambda = -0.927 \text{ or } 0.038.$$

From Equation (8): $\ddot{X} = k^2 X - eT$, as T is positive when opening the shoulder angle, for this equation to remain true, the constant e must also be positive, and k^2 will always be possible as it is a squared number.

$$\text{From Equation (9)} \quad \frac{\lambda A + B}{\lambda C + D} = \frac{E}{\left(\frac{\lambda + 1}{\lambda}\right) F} = \psi, \text{ where } e = \frac{1}{\psi m}; \text{ then } \lambda \text{ is positive then so}$$

will be the constant e . Therefore the value for λ which will be used to calculate the applied torque T will be: 0.038.

Using the chosen value of λ , from Equation (9) the constant ψ can be calculated:

$$\frac{\lambda A + B}{\lambda C + D} = \frac{E}{\left(\frac{\lambda + 1}{\lambda}\right) F} = \psi = 0.3702$$

Using the value of ψ to calculate the control parameters k and e in Equation (9):

$$\ddot{X} = k^2 X - eT, \text{ where } k^2 = \frac{g\lambda}{\psi} = 0.9992, \text{ and } e = \frac{1}{\psi m} = 0.0345$$

If $x_g - x_0 = 0$, then the handstand is balanced, and therefore $\dot{X} = \ddot{X} = 0$.

From Equation (8):

$$T = \frac{k^2}{e} X = \frac{k^2}{e} \cdot \frac{m_b x_1}{\lambda m} = m_b g x_1 = 672.27(x_1) \text{ Nm.}$$

Now repeating the process for hip control, segment UB must be added to the two arms.

Combining segment UB with the arm segment

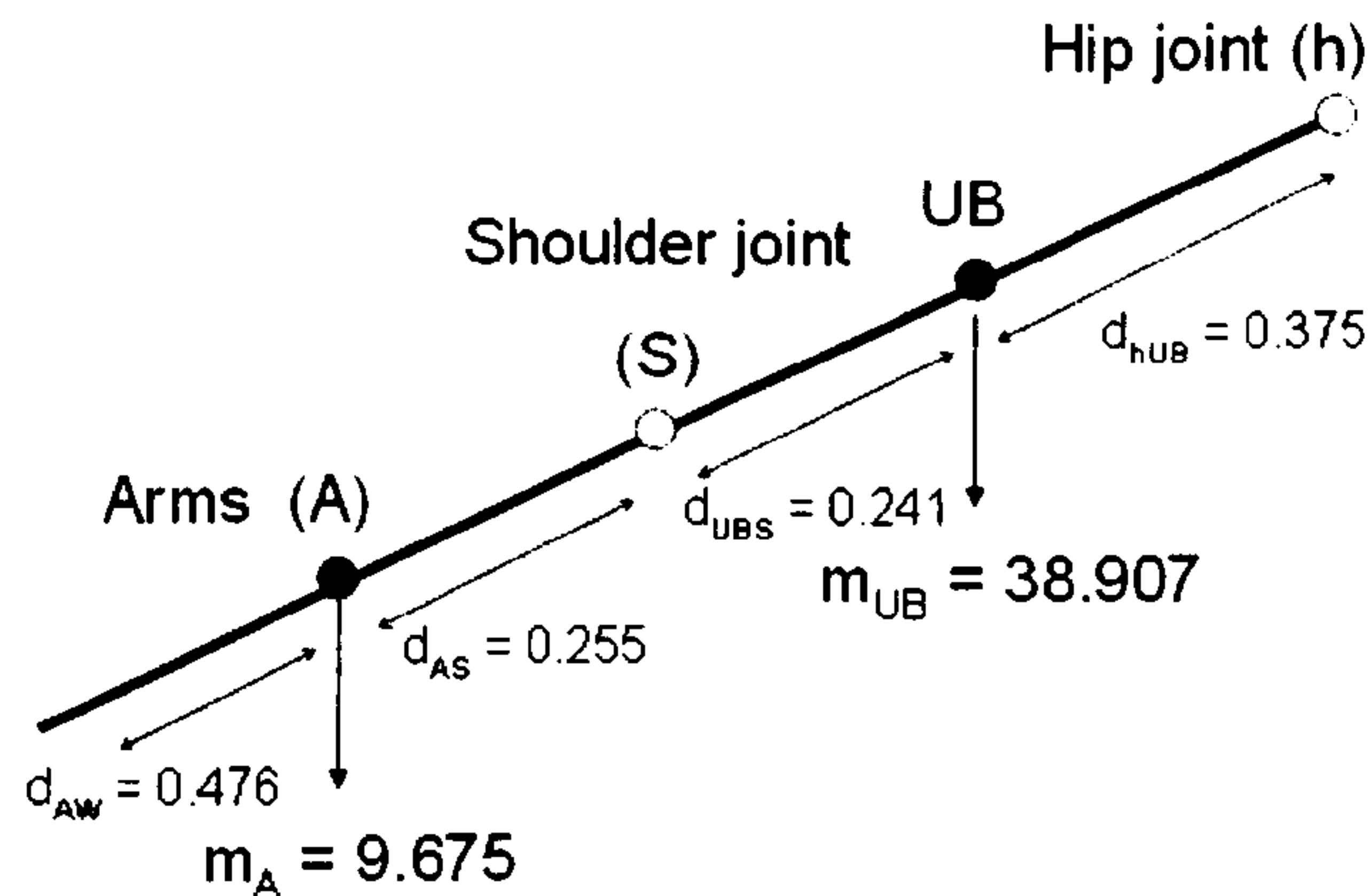


Figure 4-6: Schematic of segment A of the 2 segment handstand model.

By following the same procedure as above:

Calculating moments clockwise about h :

$$\Sigma M = (38.907 \times 0.375) + (9.675 \times (0.375 + 0.241 + 0.255)) = 23.007 \text{ kg.m}$$

Calculating the equivalent mass centre of the new segment A (Figure 4.2 and 4.6):

$$m_a = 48.582 \text{ kg}$$

The distance to the equivalent mass centre (d_a) = 0.474 m, from the h towards the shoulder.

Where:

$$\text{The distance from } UB \text{ to } m_a (d_{UB}) = d_A - d_{UBS} = 0.232m$$

$$\text{The distance from } A \text{ to } m_a (d_A) = d_{AW} + d_{AS} + d_{UBS} - d_A = 0.499m$$

Using the parallel axis theorem about the frontal axis:

$$I_a = (I_{UB} + m_{UB}d_{UB}^2) + (I_A + m_A d_A^2) = 6.928 \text{ kg.m}^2$$

Calculating the parameters in Equation (9):

$$A = I_a + \beta(L_1^2 + bL_1 + ab) + a^2 = 56.260$$

$$B = \beta(bL_1 + ba) = 14.995$$

$$C = I_b + \beta(L_1^2 b + b^2 - ab) = 11.599$$

$$D = I_b + \phi b^2 = 9.194$$

$$E = m_a a + m_b L_1 = 87.251$$

$$F = m_a b = 17.052$$

Where $\beta = \frac{m_a m_b}{m} = 18.401 \text{ kg}$, and m_a is the mass of the two arms, and m_b is the mass of segment B .

Using the quadratic function to now solve Equation (9)

$\lambda = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$, where $\lambda = -0.577$ or 8.410 . λ must be positive, therefore the value being used to calculate the torque will be: 8.410 .

Using the chosen value of λ , from Equation (9) the constant ψ can be calculated:

$$\frac{\lambda A + B}{\lambda C + D} = \frac{E}{\left(\frac{\lambda + 1}{\lambda}\right) F} = \psi = -4.5729$$

Using the value of ψ to calculate the control parameters k and e in Equation (8):

$$\ddot{X} = k^2 X - eT, \text{ where } k^2 = \frac{g\lambda}{\psi} = 18.041, \text{ and } e = \frac{1}{\psi m} = 0.0028.$$

If $x_g - x_0 = 0$, then the handstand is balanced, and therefore $\dot{X} = \ddot{X} = 0$.

From Equation (8):

$$T = \frac{k^2}{e} X = \frac{k^2}{e} \cdot \frac{m_b x_1}{\lambda m} = m_b g x_1 = 290.56(x_1) \text{ Nm.}$$

Conclusion

From the theoretical work carried out in this section, it has been demonstrated that the handstand balance on the rings may be controlled using a strategy for varying either the shoulder torque or the hip torque as a function of the horizontal displacement of the mass centre relative to the wrist and the rate of change of this displacement (Equation (10)). The proportional plus derivative function described by

Equation (10) will maintain control so long as the coefficients of the damped simple harmonic motion are positive.

From this work it has been shown that the displacements of the wrist, shoulder, hip and toe are important variables to be measured during the data collection. This information will help to provide indicators describing the control mechanism for the balance of the rings handstand for the individual gymnast. The collection of force data will enable an assessment of the reaction forces present during the skill for comparison with the floor skill, and the collection of muscle EMG will permit an assessment of muscle activation associated with the shoulder and hip torque described within the theoretical model.

By obtaining variables which are described in the theoretical model, such as joint centre movement and joint angles along with force and EMG data, a comparison between the floor and rings handstand will be possible. This comparison will further support the analysis of skills performed on the designed prototype training aid and existing training aids for the rings handstand to establish which type of handstand (floor or rings) the performances resemble. This analysis is detailed in Chapter 6.

The information obtained from the data collection during the performed balances will be used to obtain design details, such as the observed magnitudes of back and forth movement, and sideways movement of the joint centres. These details will be used to establish design dimensions, such as the area in which the gymnast is capable of performing the balance.

4.1.3 Theoretical model assessment

The initial model of the handstand on the frictionless surface, does not completely model the actual environment. The initial model discussed in Section 4.1.2, neglects to include the swing of the cable during the balance, and the restoring force introduced by the cables.

If the gymnast moves with the swing of the rings, maintaining his body mass to be inline with the cables, the restoring force of the cables will act continually trying the reposition the rings beneath the point of their suspension. This results in the gymnast and rings always returning to beneath the point of support, and consequently continues to swing. It is practically impossible to stop swing once it has begun, and the swing will generally be initiated through a poor entry to handstand. During a still

handstand it is equally hard to initiate significant swing, especially through balance controlling arm movements.

To accomplish the design of a training aid to help learn a handstand on the rings, the environment in which the handstand is to be learnt must closely simulate the real environment of the rings. It will therefore be necessary to replicate the modelled 'frictionless' environment as closely as is possible in order to design a suitable training aid. To justify this, the 'real' environment of the rings will need to be compared to that of the training aid. In the diagram (Figure 4.7) below can be seen two models:

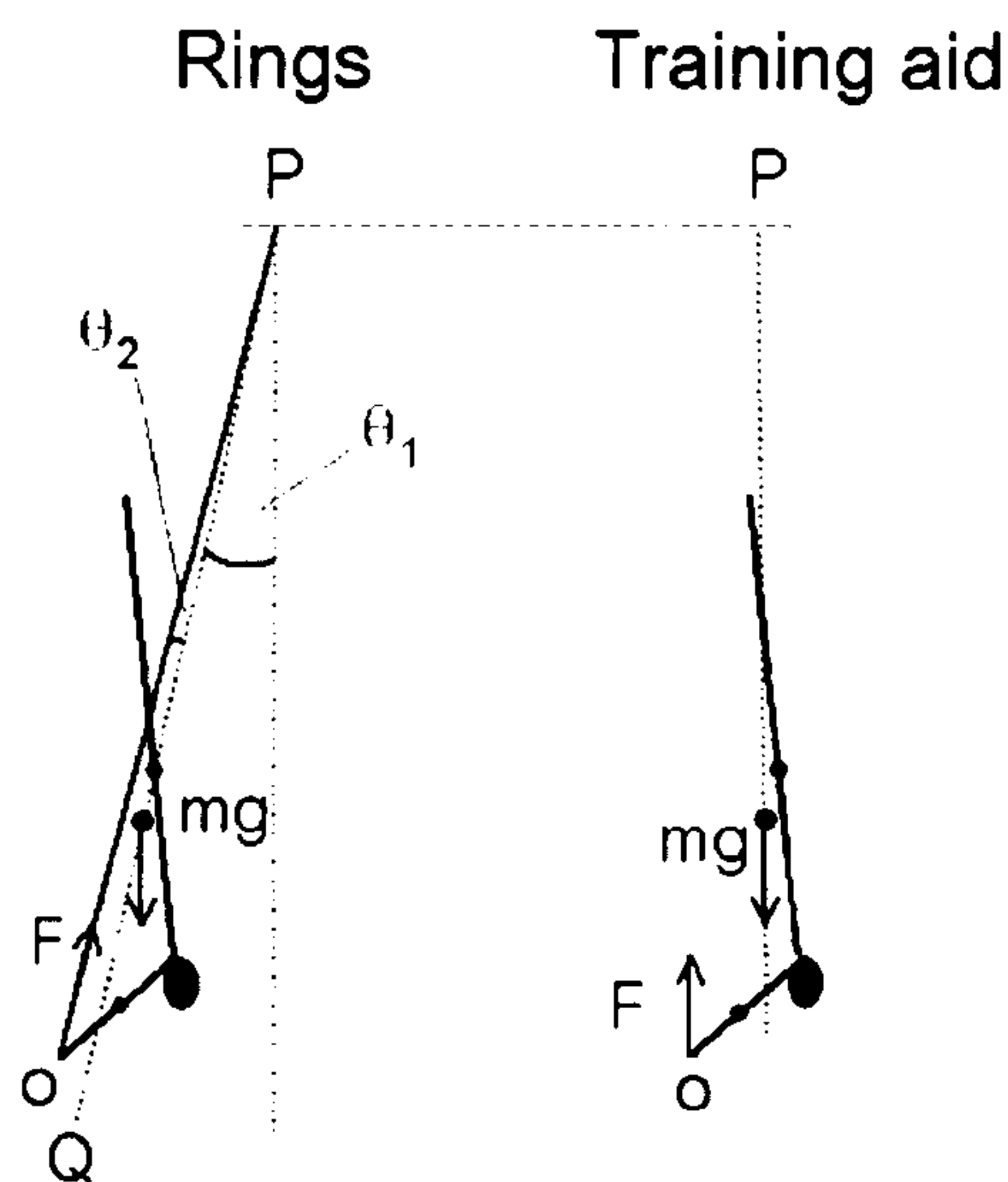


Figure 4-7: Comparison of the rings model and the training aid model.

To analyse the model of the rings, first consider a moving reference frame PQ, and introduce fictional forces $mr\dot{\theta}^2$ and $m(r\ddot{\theta} + 2\dot{r}\dot{\theta})$ radially and tangentially.

Using Newton's 2nd law: Resolving parallel to P-Q for the rings model:

$$F \cos \theta_2 - mg \cos \theta_1 = mr\dot{\theta}_1^2 - m\ddot{r} \quad (15)$$

For the training aid model:

$$F - mg = -m\ddot{r} \quad (16)$$

Equations (15) and (16) are very similar, except that Equation (15) also has the effects of θ_1 and θ_2 . Therefore if $F \cos \theta_2$ is approximated to be equal to F , and $mg \cos \theta_1 + mr\dot{\theta}_1^2$ is approximated to be equal to mg , then the deviation from this approximation can be calculated to establish the similarity of the two models.

Resolving perpendicular to P-Q for the rings model:

$$F \sin \theta_2 + mg \sin \theta_1 = -mr(\ddot{\theta}_1) - 2m\dot{r}\dot{\theta}_1 \quad (17)$$

but equivalently $\ddot{X} = 0$, since $X=0$ in the moving reference frame.

For the training aid model:

$$m\ddot{x} = 0 \quad (18)$$

Consequently the tangential equation of motion is the same for the rings in this reference frame and for the training aid.

By comparing both the forces involved in the model of the rings at the bottom and maximum of the swing to the forces present in model of the training aid:

Considering θ_1 : $mg \cos \theta_1 + mr\dot{\theta}_1^2 \equiv mg$, dividing by mg gives: $\cos \theta_1 + \frac{r}{g}\dot{\theta}_1^2 \equiv 1$,

where at maximum swing angle velocity will equal zero, and at the bottom of the swing where the angle is zero, the velocity will be a maximum.

Considering θ_2 : $F \cos \theta_2 \equiv F$, therefore dividing by F gives: $1 - \cos \theta_2 \equiv 0$

Establishing a minimum and maximum value for θ_1 : From Yeadon and Brewin (2003), from the Olympic data analysed the expected minimal residual cable angle is 2° (0.035rad) and a considerable swing is 7° (0.122rad).

With the rings having a suspension length of 3m using the equation: $s = r\theta$, corresponds to an equivalent rings movement of $\pm 0.105\text{m}$ and 0.336m respectively. (Figure 4.8).

Using Pythagoras for the minimum angle:

$$x^2 = 3^2 - s^2$$

$$x = \sqrt{9 - 0.105^2}$$

$$x = 2.99816$$

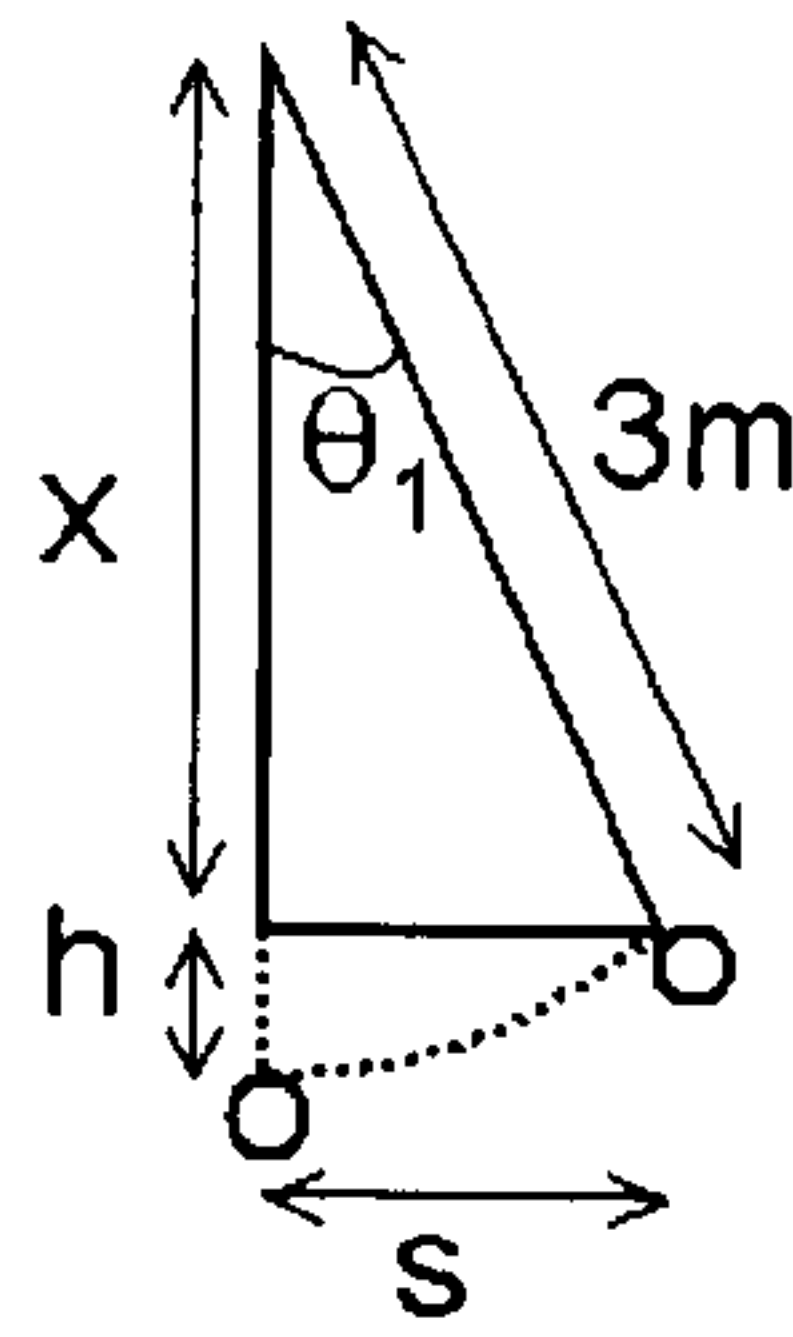


Figure 4-8: Pythagoras triangle representing movement of the rings.

Calculating the rise of the rings, h :

$$h = 3 - x$$

$$h = 0.0018m$$

As energy is conserved, the height gained in the swing will result in the magnitude of velocity at the bottom of the swing, therefore:

$$mgh = \frac{1}{2} mv^2$$

$$v^2 = 2gh$$

$$v = 0.1899 \text{ ms}^{-1}$$

For motion in a circle, with the mass centre 0.9m above the hands at a radius of 2.1m:

$$\dot{\theta}_1 = \frac{v}{r} = \frac{0.1899}{2.1} = 0.0904s^{-1}$$

Comparing the forces for a θ_1 value of 0.035 rads:

$$\text{At the top of the swing: } \cos \theta_1 = \cos(0.035) = 0.9994 \equiv 1 - 0.0006.$$

$$\text{At the bottom of the swing: } \frac{r}{g} \dot{\theta}_1^2 = + \frac{2.1}{9.81} (0.0904)^2 = 0.00175.$$

As the percentage fictitious force varies from 0.0006 to 0.00175 of mg , the maximal percentage force is 0.18% (2.d.p). Now repeating the process for the maximum swing angle:

Using Pythagoras:

$$x^2 = 3^2 - s^2$$

$$x = \sqrt{9 - 0.112^2}$$

$$x = 2.99791$$

Calculating the rise of the rings, h :

$$h = 3 - x$$

$$h = 0.0020m$$

Through the conservation of energy:

$$mgh = \frac{1}{2} mv^2$$

$$v^2 = 2gh$$

$$v = 0.2026 \text{ ms}^{-1}$$

For motion in a circle, with the mass centre at a radius of 2.1 m:

$$\dot{\theta}_1 = \frac{v}{r} = \frac{0.2026}{2.1} = 0.0964s^{-1}$$

Comparing the forces for a θ_1 value of 0.112 rads:

At the top of the swing: $\cos \theta_1 = \cos(0.112) = 0.9937 \equiv 1 - 0.0063$.

At the bottom of the swing: $\frac{r}{g} \dot{\theta}_1^2 = + \frac{2.1}{9.81} (0.2026)^2 = 0.0088$.

As the percentage fictitious force varies from 0.0063 to 0.0088 of mg , the maximal percentage force is 0.88% (2.d.p). For both the minimum and maximum cable angles $mg \cos \theta_1 + mr \dot{\theta}_1^2$ is less than 1% of mg .

With details taken from information collected during the data collection in Section 4.2, minimum and maximum values for θ_2 can also be compared between the two models. The minimum shoulder movement calculated was $\pm 3.8^\circ$ (0.066rad), and the maximum was measured to be $\pm 9.1^\circ$ (0.1588).

Comparing the force for a θ_2 of 0.066 radians:

$$1 - \cos(0.066) = 1 - 0.9978 = 0.00219$$

Comparing the force for a θ_2 of 0.1588 radians:

$$1 - \cos(0.1588) = 1 - 0.9874 = 0.01259$$

As a percentage, these calculations give a value of 0.21% (2.d.p) for minimum θ_2 , and a percentage of 1.26% (2.d.p) for maximum θ_2 .

Results

Since $mg \cos \theta_1 + mr \dot{\theta}_1^2$ is within 0.9% of mg for even a maximal movement of the rings, and $F \cos \theta_2$ is less than 1.3% of F for even maximal shoulder movement, this shows that the two models have approximately the same radial forces. The resulting model for the rings has $\ddot{x} = 0$ since the reference frame moves with the mass centre, which is the same as for the training aid model, therefore the two models have similar forces and dynamic movements.

The swinging motion of the rings was found to have a period of around 3 seconds. Superimposed upon this motion is the short-term correction around the swing. This correction has the same form as the control for the model of the training aid movement. Thus to a first approximation the same control is used in both cases.

4.2 Data collection

This section will detail the methodology of the data collections performed. Experimental set ups will be explained and procedures will be discussed.

4.2.1 Introduction

There have been several studies in which forces within rings cables have been measured using force transducers during the performances of gymnastics skills: for example the work carried out by Brewin (1999). These studies have also continued the investigations, to develop simulation models of gymnastic skills rather than using the data to design a physical training aid to help gymnasts learn the skill. As mentioned earlier, there are no specific studies about the handstand on rings, but some of the reviewed studies of the rings will be used and adapted for the following data collection procedure. The following section will contain details of the investigative work carried out in preparation for the main data collection procedure.

4.2.2 Pre testing

To establish the requirements for the collection of Vicon, load cell and EMG data of a handstand on the rings, several pre-tests were carried out on the various pieces of equipment.

Strain Gauges and Load Cells

Strain gauges are one of the most accurate, sensitive, versatile and easy to use sensors available (Window, 1989). The majority of foil strain gauges are required to be laminated onto a rigid surface as they are precision rolled to an exact thickness of typically 0.003 to 0.005mm. This laminated backing must be suitable for the required purpose of the strain data to be collected. In the rings study carried out by Yeadon and Brewin (2003), load cells were produced by laminating a pair of strain gauges onto a flat steel bar, which in turn had holes drilled at either end to allow the load cell to be connected with karabiners in series with the rings cable.

If only a force relationship is required rather than an actual strain value, the gauge factor can be used as a sensitivity control to be optimised for the data collected. If strain is required, then the gauge factor for the bonded strain gauge is required, which is dependent on the metallurgical condition of the alloy from which the grid is manufactured, the gauge grid size and various other parameters. The gauge factor will be provided by the manufacturers of the strain gauge.

The first test procedure in this data collection was to establish the sensitivity of the load cells in order to determine if they would detect the tiny adjusting motions of the hands during the control of a high-quality handstand balance on the rings.

The load cells were constructed from 25mm wide mild steel plate, with a thickness of 3mm, and a length of 150mm. To the centre on both sides of this plate, were bonded two 120 Ohm foil strain gauges, type FCA-3, cross paired at 90° to each other, (grid dimension: 3.0mm by 1.5mm), made by Techni Measure Limited. As the two strain gauges were cross paired, one underwent compression, whilst the other was in tension, and the pair was wired to form a full Wheatstone bridge. Two karabiners were attached to the plate in order to place the load cell in series with the rings cable, as can be seen in Figure 4.9 below.

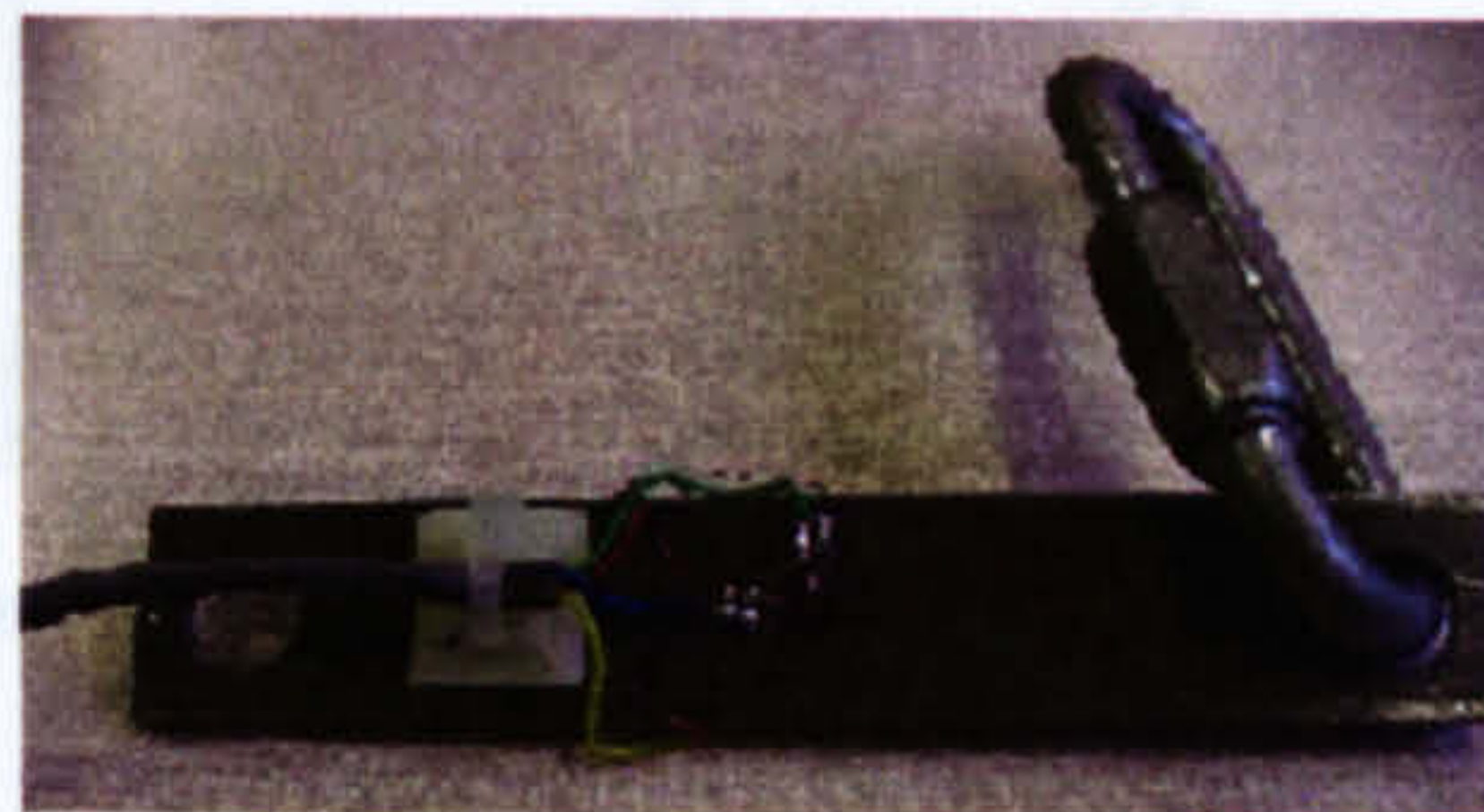


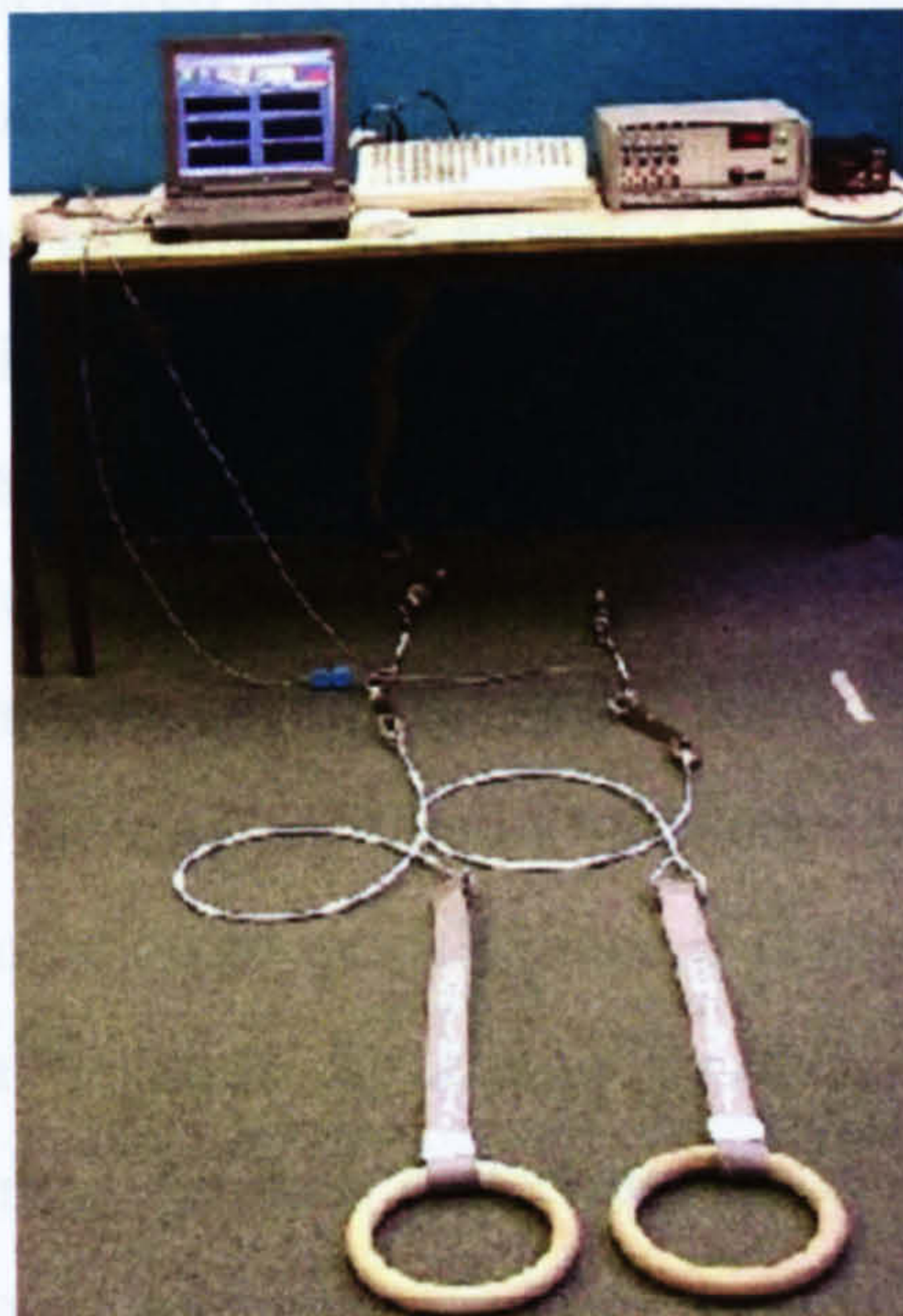
Figure 4-9: A load cell.

The output from the load cell was amplified by a Modular 600, 12V 4 channel SG Amplifier, produced by RDP Electronics Ltd, with a power of 75W. The

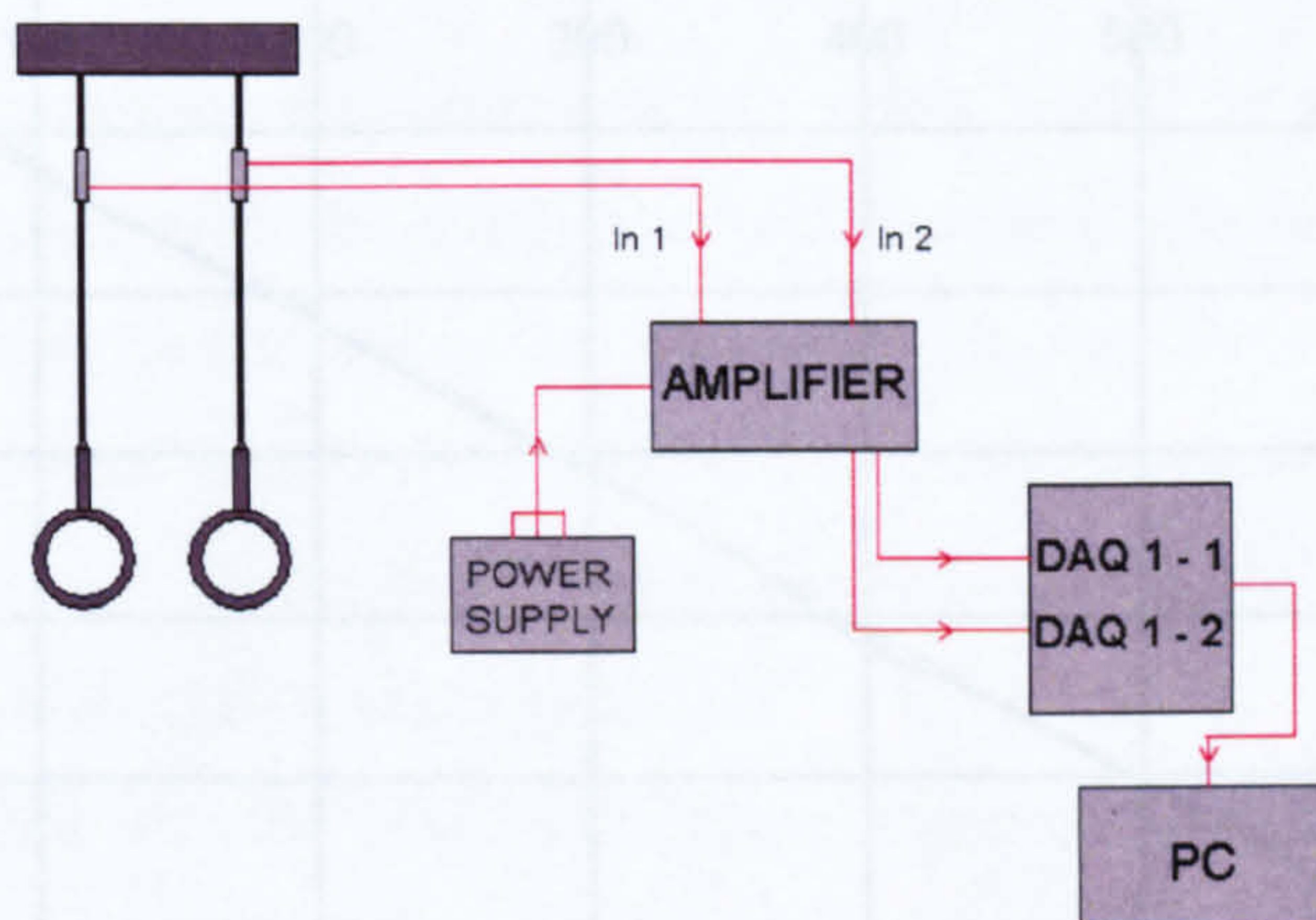
amplifier had an adjustable gauge factor, the affects of which were investigated during the initial testing of the load cells. The amplifier was connected to a regulated DC power supply unit, Sharman Multicom Ltd, PS-3 model with an input voltage of 240V, 50Hz and 60W, and an output of 13.8V DC. Figures 4.10 and 4.11 show the details of this set up.



Figure 4-10: Amplifier and power supply connected to the PC.



(a)



(b)

Figure 4-11: Experimental set up for load cell calibration and testing.

The system was controlled through a National Instruments DAQ card A1-16XE-50, and a PC through which the data was collected, observed and saved for further analysis at a future date.

Before the testing of the full set-up could commence, the load cells had to be tested on their own. The first testing to be carried out on the load cells was their calibration. This was carried out on a Lloyd Instrument LXR material testing machine, with a resolution of 0.04N and a capability of loading samples up to 1000N (Lloyd Instruments, 2004).

The load cells were locked into position on the machine test bed and incremental loads were systematically added to the sample. The load cells were initially loaded with 45.5N and this was then increased in approximate 50N increments (which were measured accurately to 0.05N) up to a loading of 660.0N. The load cells were then unloaded back down to 44.9N in similar increments. The gauge factor and gain of the amplifier was adjusted to maximise the ± 10 volt scale to ensure that all data was collected without clipping. This would ensure that no relevant data was lost, but that the scale was used to a maximum range. Very little hysteresis was observed during the loading-unloading cycle which meant that during multiple tests when the gymnast would mount and dismount the rings between trials, hysteresis within the system could be ignored. A graph of this data can be seen below in Figure 4.12. Measurements had to be taken quickly since if the load was held constant for a prolonged time the material began to retract slightly altering the strain reading. This will not be a problem during the data collection however as the gymnast will be continually moving, therefore altering the loading continually.

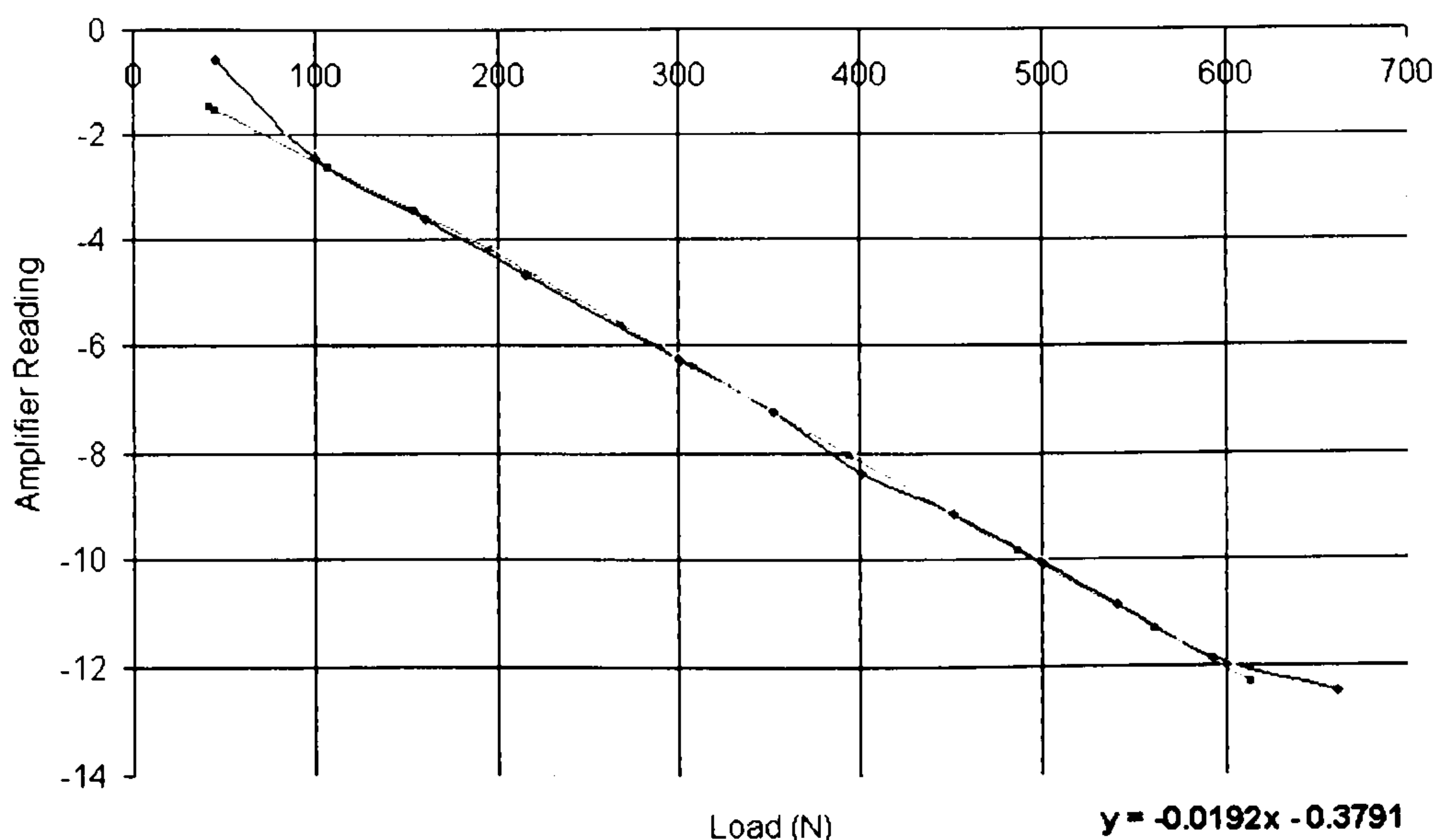


Figure 4-12: Graph of load cell calibration loading pattern.

A reduced scale was then implemented for fine adjustments on loading. The load cell was loaded from 319.5N up to 418.5N in approximate 10N increments. This was to obtain a more accurate graph of the relationship of loading against strain for the expected working range during the full data collection procedure. The data collected during this procedure was graphed, and is detailed in Figure 4.13.

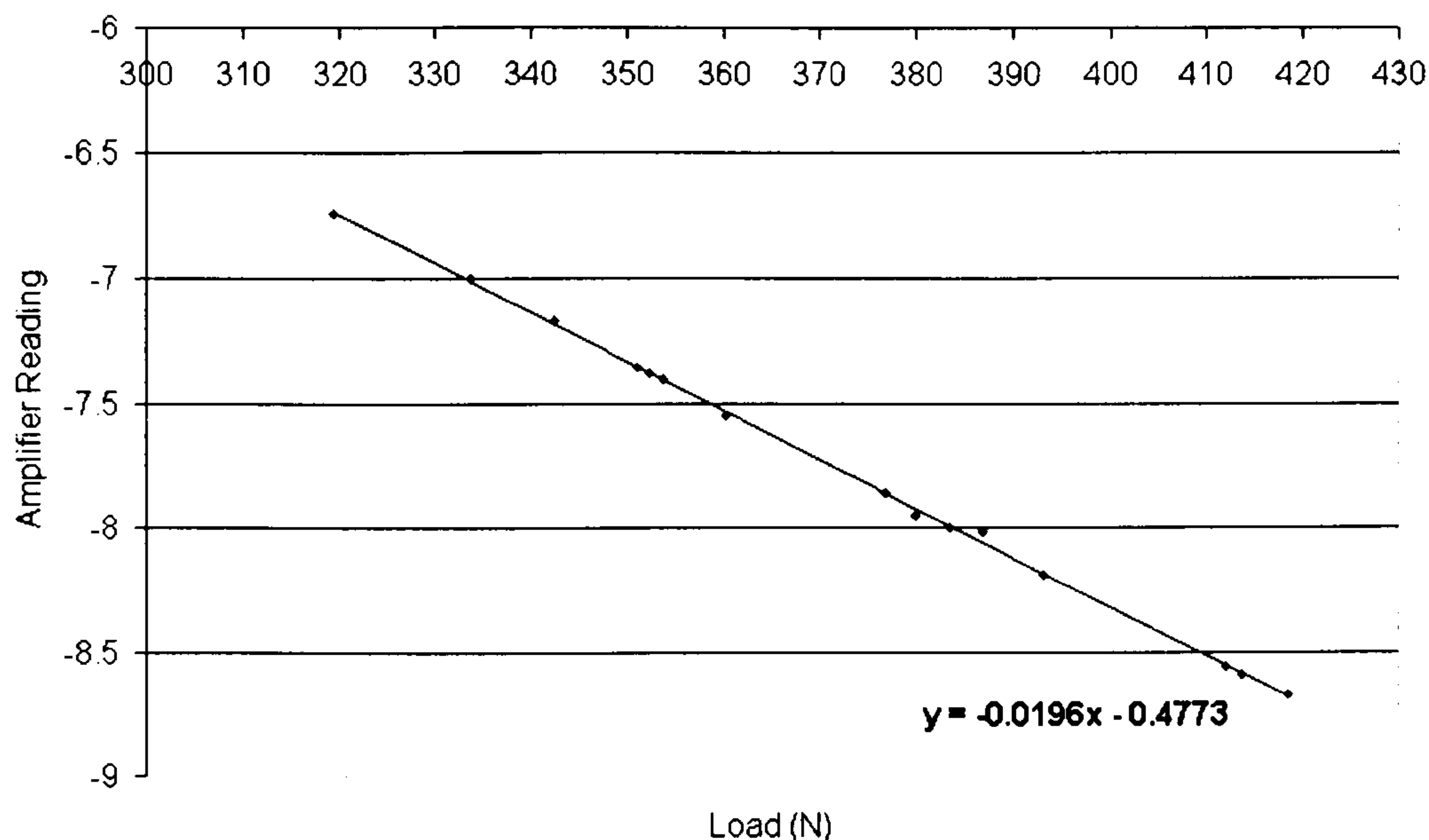


Figure 4-13: Graph of reduced loading load cell calibration loading pattern (35 kg).

Once calibrated, the sensitivity of the load cells needed to be tested. If any of the small balance control adjustments were to be detected by the load cells, the gauges would need to be zeroed with respect to the weight of the gymnast. Any differences detected within the load cell reading would therefore be due to the gymnast moving to maintain balance.

Since the controlling movement of the wrists would be small, the angle the rings cable would make with the vertical would therefore also be small, introducing only small differences detected by the load cell. It was for this reason that the sensitivity of the load cell had to be established. For this calculation, the load cell was zeroed at a load of 35kg. Increments of approximately 10N loads were systematically added to and then subtracted from the load cell.

It was decided that the minimum forces observed would occur if only slow swing movement was present, rather than any fast active movement from the gymnast. In this situation the gymnast and rings could be modelled simply as a swinging pendulum (Figure 4.14).

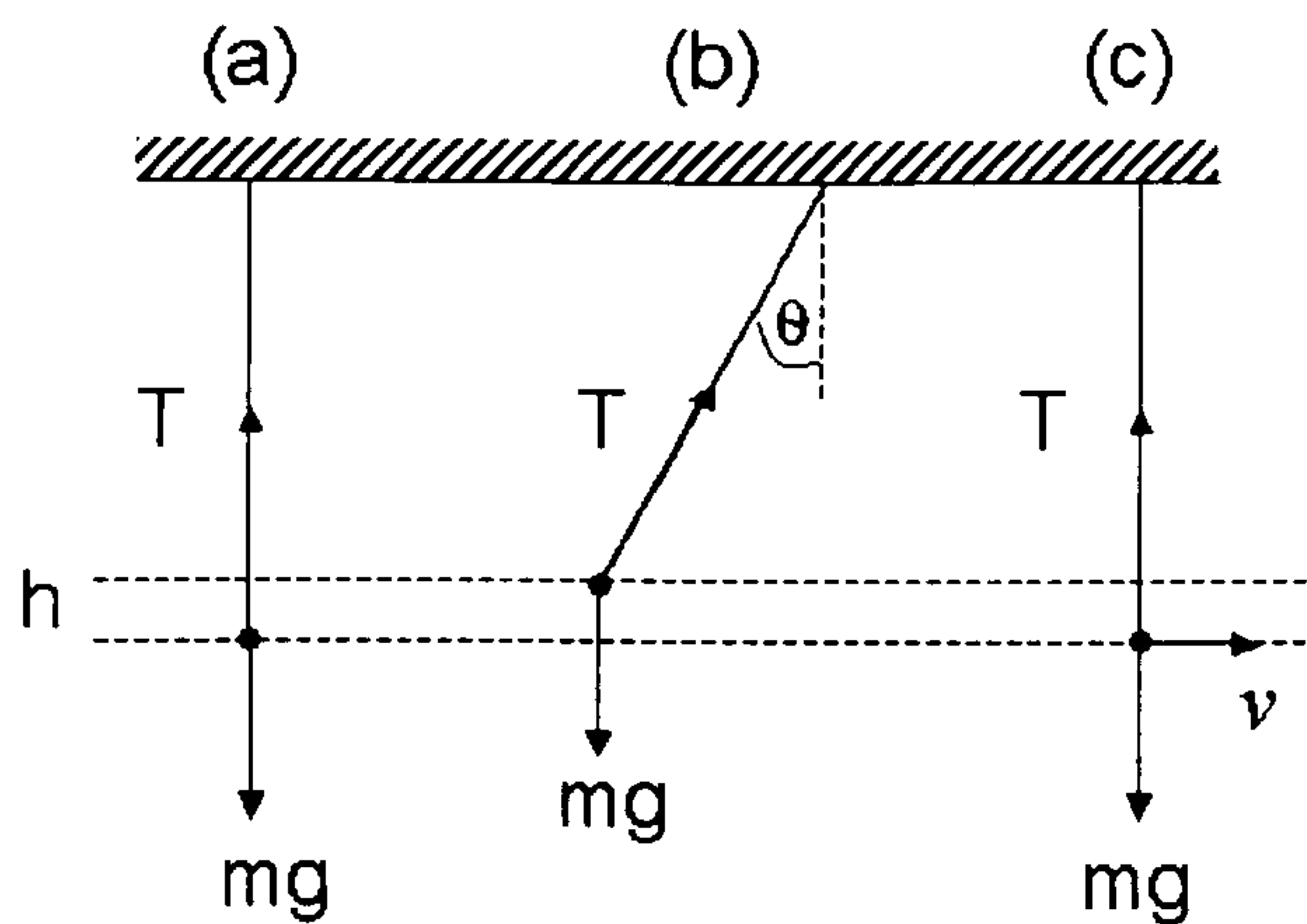


Figure 4-14: A simple pendulum: (a) stationary (b) top of the swing (c) bottom of the swing.

For (a) $T = mg$; for (b) $T = mg \cos \theta$ as at the top of the swing, the velocity is equal to zero; for (c) $T = (mv^2/r) + mg$, where v is the velocity of the mass centre. To establish if the sensitivity if the load cell was sufficient, the following question was asked: *If the gymnast has a body mass around 70kg, the length of the rings and cable combined is three metres, and the centre of mass is 0.9 metres above the hands, then if his hands were to move approximately 100mm during slow swing, what would be the difference in the cable tension between the top and the bottom of the swing? Assume the gymnast stays in line with the rings, and that the shoulders remain open (see Figure 4.15).*

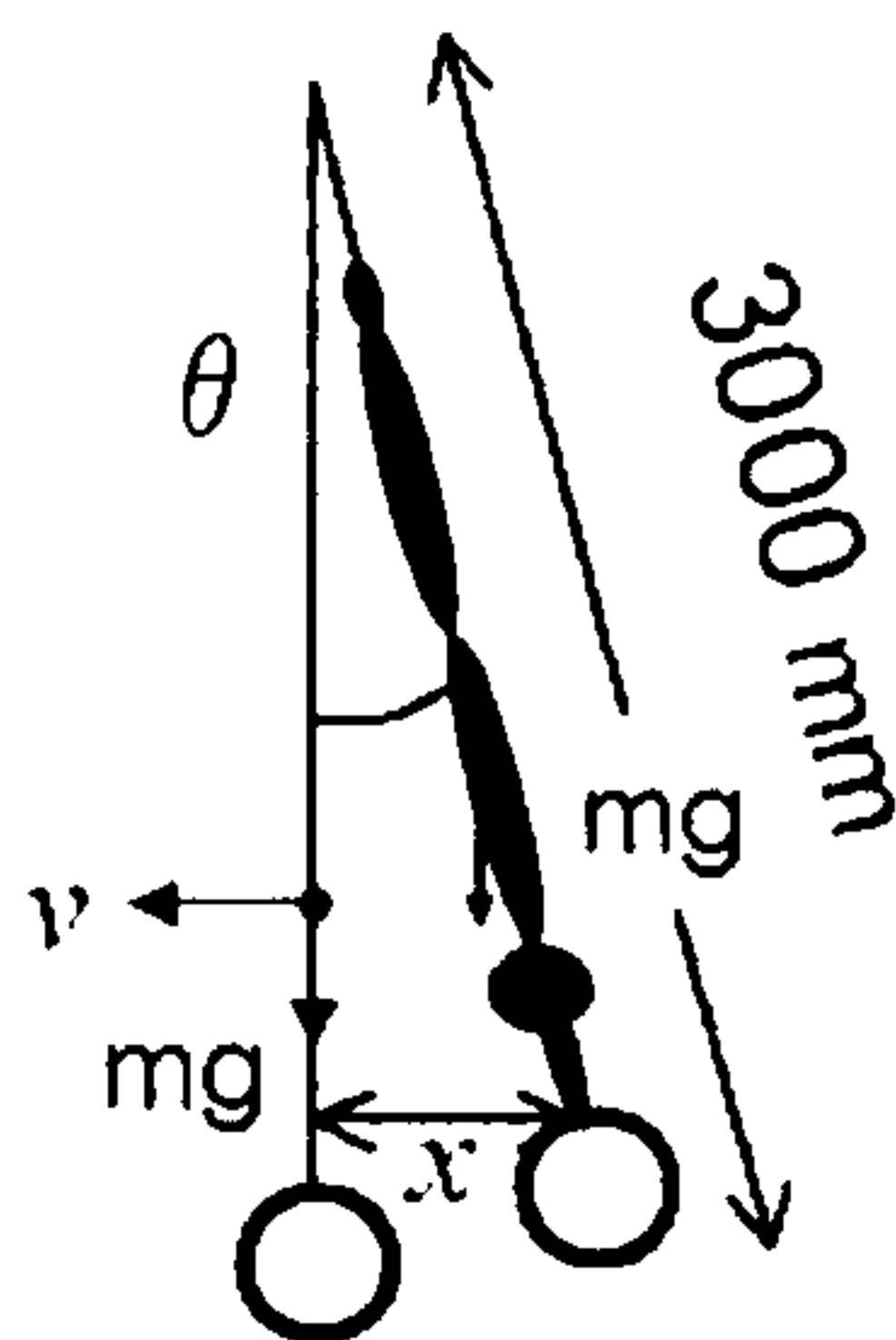


Figure 4-15: The rings scenario.

To calculate the velocity at the bottom of the swing, the conservation of energy must be considered: $mgh = \frac{1}{2} mv^2$, from Figure 4.12, 'h' is the amount the rings will rise during the 100mm horizontal movement.

At the bottom of the swing:

Using Pythagoras: $h = 3000 - \sqrt{3000^2 - 100^2} = 0.017\text{mm}$ (3.d.p).

Calculating the velocity: $mgh = \frac{1}{2}mv^2 \therefore v = \sqrt{2gh} = 0.013\text{m/s}$ (3.d.p)

The cable tension is therefore: $T = (mv^2/r) + mg = \frac{70 \times (0.013^2)}{2.1} + (70 \times 9.81) = 686.71\text{N}$.

At the top of the swing:

The angle $\theta = \sin^{-1}(3000/100) = 1.91^\circ$ (2.d.p)

The cable tension is therefore: $T = mg\cos\theta = 70 \times 9.81(\cos 1.91) = 686.31\text{N}$.

Therefore the difference in the cable tension between the top and the bottom of the swing is 0.4N for small quantities of slow swing. This will be greatly increased when also considering the movements introduced by the gymnast controlling the balance as those actions will also involve accelerations. The sensitivities of the strain gauges were measured, and it was found that they were capable of sensing these alterations in tension.

This calibration work would now permit an accurate conversion between the strain measured by the gauges, and the overall movement of the rings cable through all three axes of movement. The end resultant movement of the wrists would be obtained using Pythagoras calculations (see Figure 4.16 below).

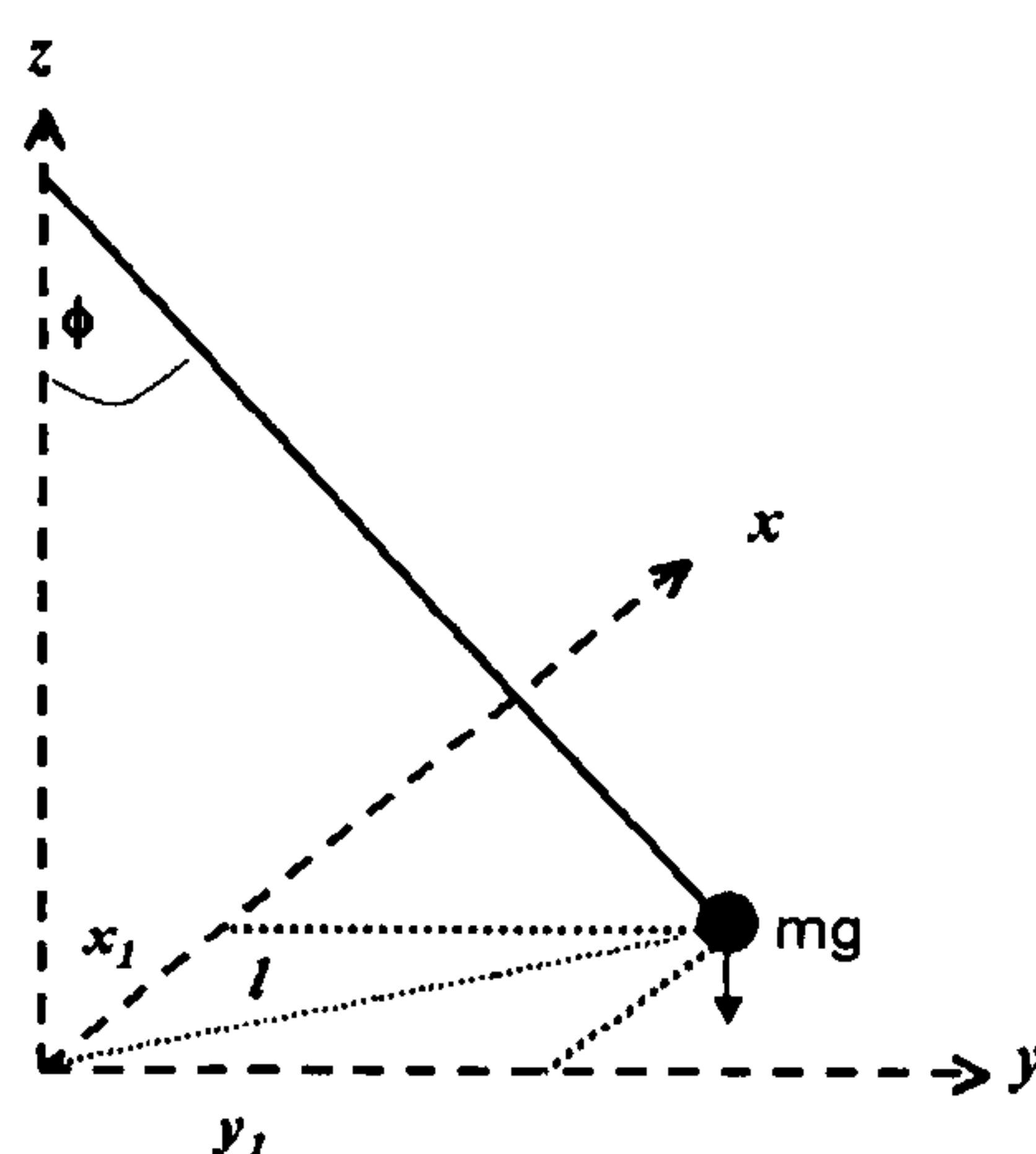


Figure 4-16: Pythagoras description of ring location in x-y plane.

Where: $l = \sqrt{x^2 + y^2}$

Once fully calibrated and tested for sensitivity, the load cells were re-attached in series with the rings cables, and these were suspended from a metal support beam. In this location increments of 5kg were added to the two cables, with the load

suspended from the ring. Weights were added up to 65kg which was significantly higher than any load expected to be applied during the full data collection. This procedure was then repeated for the other ring.

The reason that this experiment was performed was to obtain data on the gauges in series with the cables. As the cables would stretch slightly during loading, it was important that this effect was measured, although no difference in load cell reading was expected. This procedure was then also carried out with the rings in situ suspended from the rings frame, in order to see how the system responded in its entirety, with flexion of the frame, extension of the cables, and elongation of the load cell. As all of these individual components will act like a series of springs (Figure 4.17), each will have its own spring constant and so add to the downward displacement of the system, but as the load cells are measuring force, no differences should be observed from the results taken.

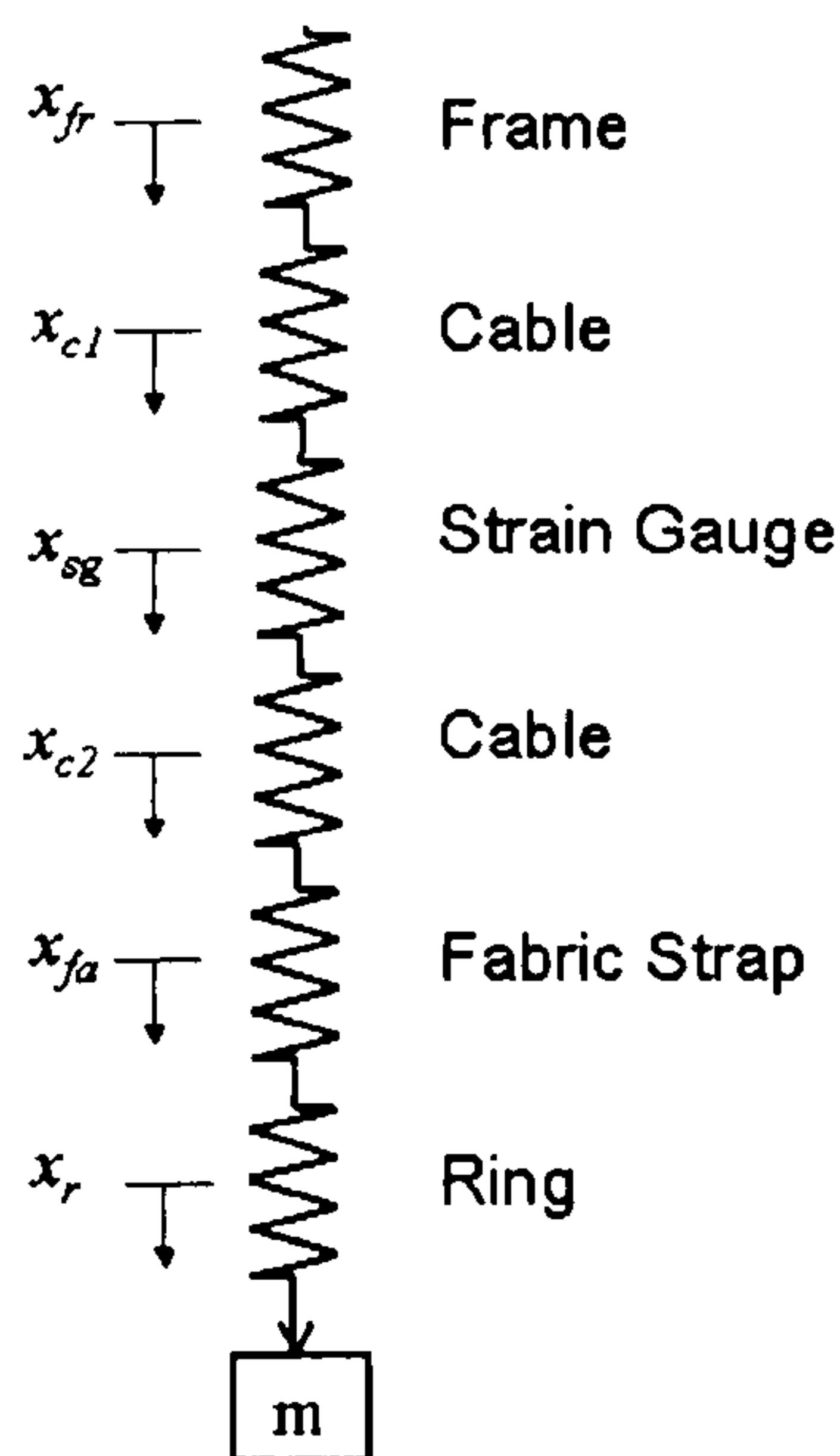


Figure 4-17: Series of springs within the rings apparatus.

Where: $F = -k_{fr}x_{fr} = -k_{c1}x_{c1} = -k_{sg}x_{sg} = -k_{c2}x_{c2} = -k_{fa}x_{fa} = -k_r x_r$, and k = spring constant, and x = displacement.

Figure 4.18 details the relationship between strain and load for the rings when loaded in situ.

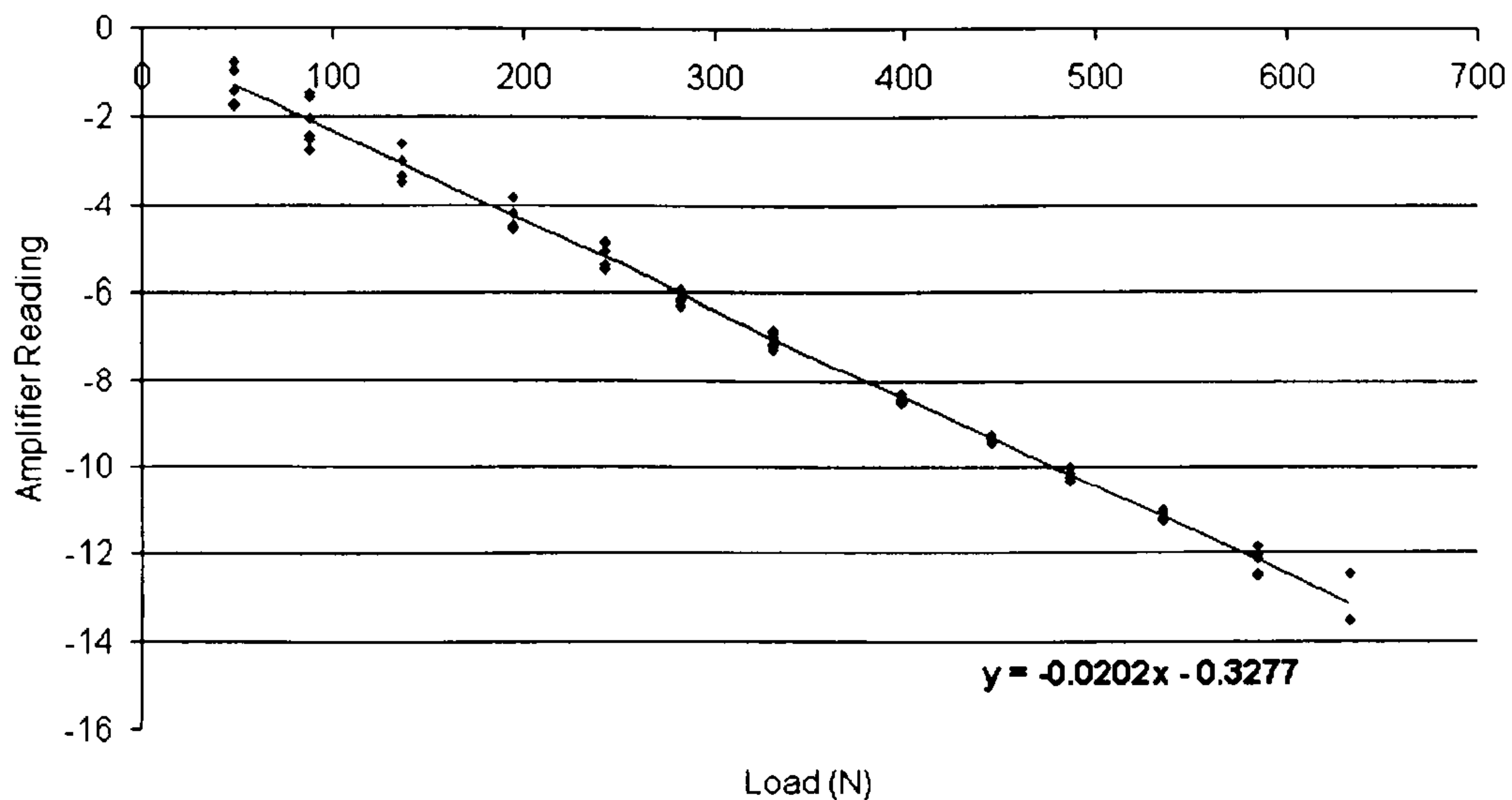


Figure 4-18: Rings loading on full rings frame.

It can be seen that the two rings calibration graphs (Figure 4.13 and 4.18) have gradients of -0.0196 and -0.0202, and therefore as expected the full rings apparatus had no significant affect on the reading produced by the load cells. Again, during this study only minimal hysteresis was observed, and so this phenomenon can be assumed to be negligible during the full data collection procedure.

Vicon

The Vicon Motion System is designed to track human or other movement in a room-size space. Kapur et al (2005) explain that spheres covered with retro-reflective tape, known as markers, are placed on visual reference points on different parts of the human body. The Vicon system consists of multiple cameras and is designed to track and reconstruct these markers in 3-dimensional space. During capture the coordinates of all of the markers in each camera's view are stored in a data station. The Vicon system then links the correct positions of each marker together to form continuous trajectories, which represent the paths that each marker has taken throughout the capture, and thus how the subject has moved over time.

The Vicon system used consisted of a Vicon 624 Motion Capture Data-station, eighteen 1280 by 1024 pixel MOS infrared M2 cameras with an aspect ration of 5:4, eight of which were long-zoom cameras (Figure 4.19), with 24-70 mm zoom lenses, and ten of which were short-zoom, 17-35mm zoom lenses cameras. Six 3-port 1.3 million pixel M2 camera interface units connected the cameras to the data-station, and a host workstation.



Figure 4-19: Vicon M2 camera.

The first work to be carried out with the Vicon system was to establish how to use the operating system, how to capture data, how to reconstruct 3-D coordinates, and then how to extract the displacement data and export it into Excel for analysis. Once the general operations of Vicon were understood, it was important to ascertain where within the captured volume the Vicon system considered to be the origin (0, 0, z). It was not necessary to establish the z coordinate as the height of the markers was not important to the investigation.

For this procedure, three short range cameras were used, and the triangular static calibration frame (Figure 4.20). As the exact dimensions of the static calibration frame, and the orientation of the retro-reflective markers were also known, asking Vicon to output positional data on the markers allowed the position of the origin to be determined. Through this process it was confirmed that origin was the tip of the right-angled corner of the calibration frame.

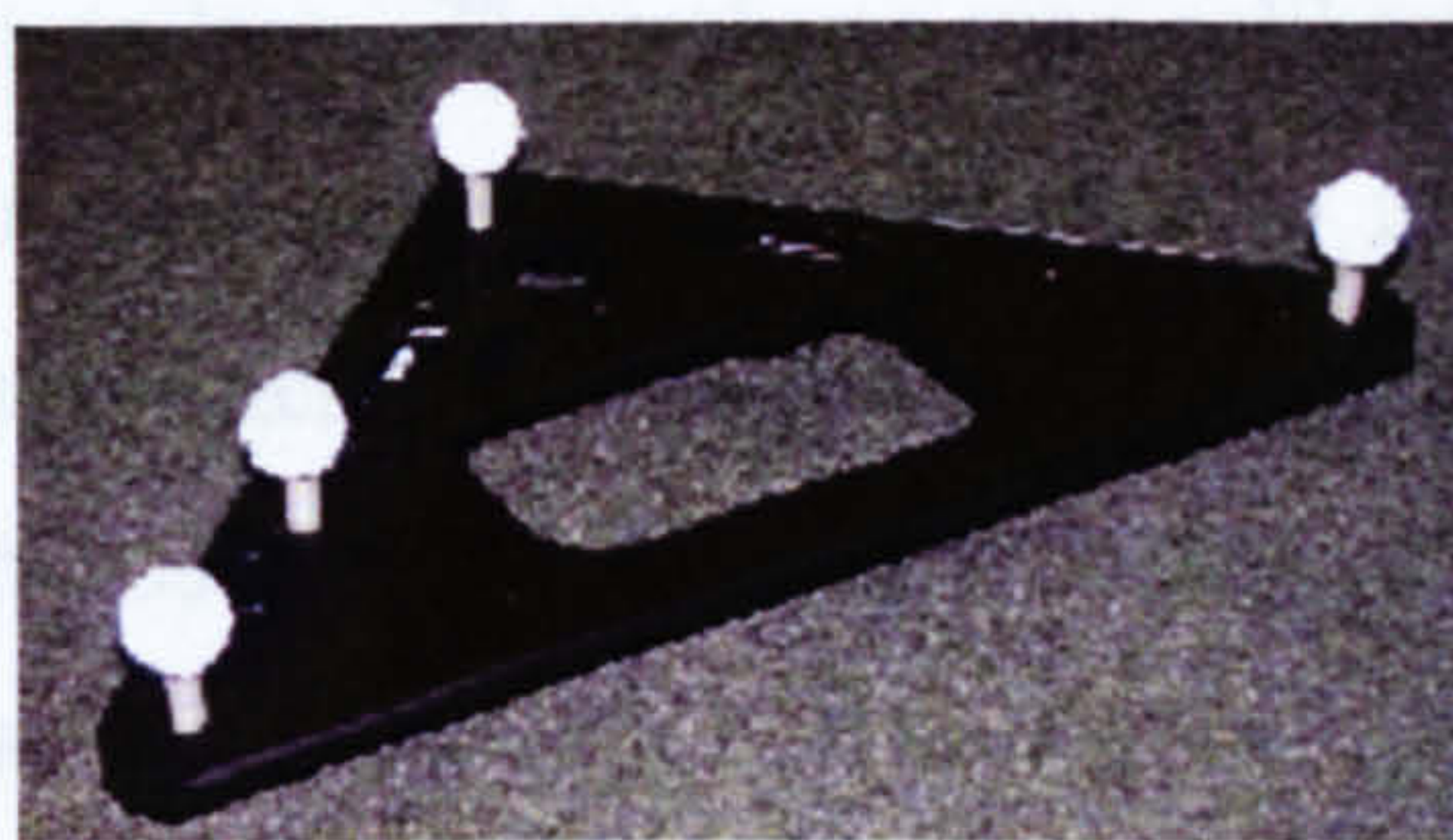


Figure 4-20: Static calibration frame.

The next step was to place the cameras around the balcony of the gymnastics centre, positioned and orientated to get the clearest view of the rings. All 18 cameras were used and positioned to achieve not just an unobstructed view of the rings, but also to optimise the distance of the camera from the rings. To do this, the long range cameras were positioned at the farthest points from the rings, with the short range cameras as close to the rings as possible. The capture volume of interest (Figure 4.21) around the rings was a tall cuboid, therefore to increase the resolution of the image,

the long lens cameras were turned on their side to increase the number of vertical pixels in use.

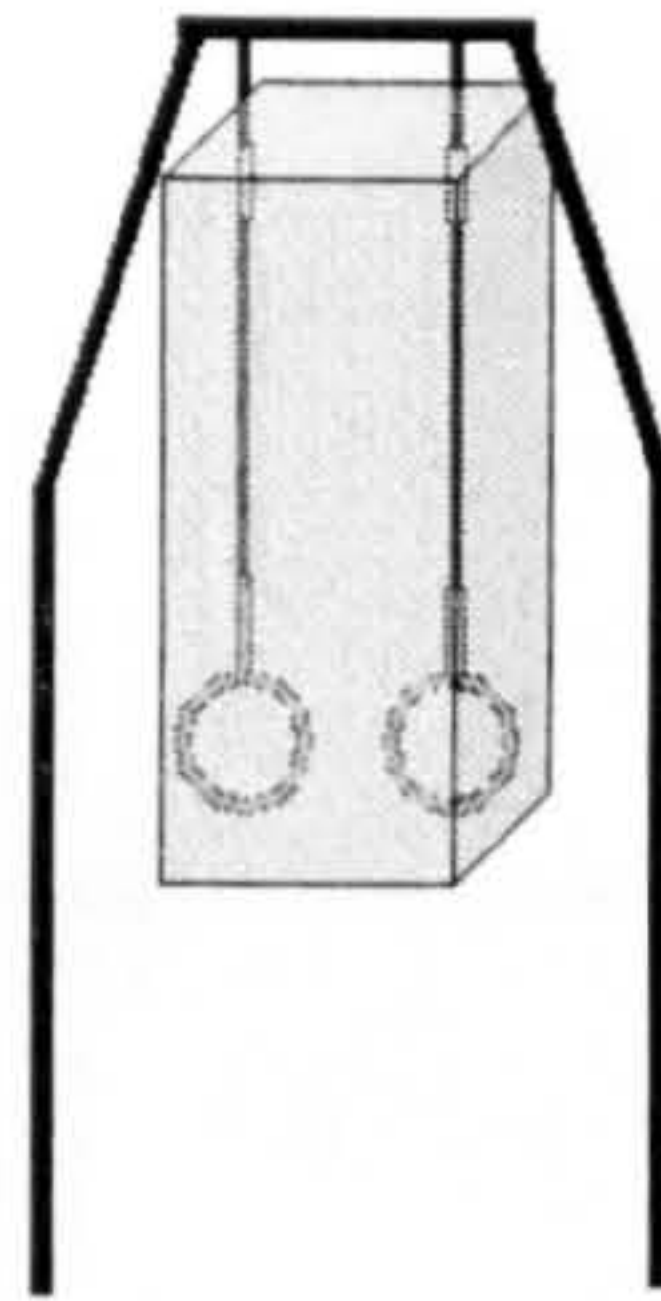


Figure 4-21: Rings Vicon capture volume.

Once positioned, and with the system set up to collect data at 100Hz, static and dynamic calibrations were performed. Cameras were finely adjusted, and positions finalised until the mean residuals, residual range and static reproducibility were optimised. The reconstruction is the calculation of the three-dimensional position of each marker in each frame using two-dimensional data from each camera (Vicon, 2002). The mean residual is a average error measured from the system reconstructed trajectories; the residual range is the maximum and minimum error of the reconstructed trajectories; the static reproducibility is the capability of the system to reproduce the static trial from the data collected. For an accurate reconstruction of a volume, it is required that 12 of the 18 camera calibration residuals need to have a maximum error of 2.0mm or less. The volume was calibrated so that the data from forward and backward rings movement corresponded to the x-coordinate, and data collected from sideways movement corresponded to the y-coordinate of the positional data obtained. The system was now ready for data collection.

A single trial was then carried out collecting data on just the markers positioned on the rings cables. During the collection of this data set a single square pulse wave was sent to the analogue port on the Vicon data-station to ensure that an analogue signal could be detected and saved during the collection of Vicon data. The analogue pulse was required in order to synchronise the EMG, load cell data and Vicon data during the full data collection.

EMG

Konrad (2005) explained that EMG permits you to look directly at the muscle allowing analysis to improve sporting activities. When recording a raw EMG signal, a

graph is produced of muscle voltage output (generally to the magnitude of millivolts) against time (Figure 4.22).

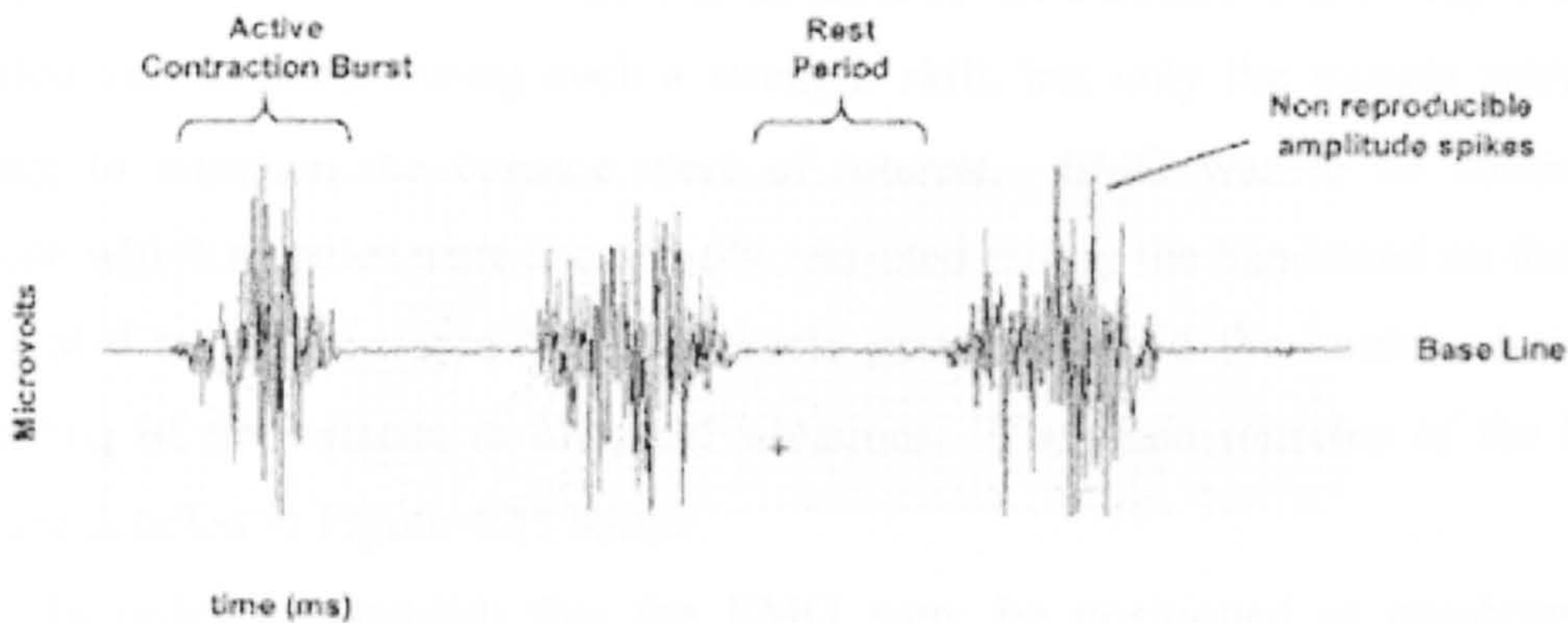


Figure 4-22: Example of raw EMG data (adapted from Konrad, 2005).

For best results the electrodes need to be placed in parallel to the muscle fibre over the middle portion of the muscle belly as the clearest signal is observed here; such anatomical landmarks are recommended in Konrad (2005). Maximum voluntary contractions performed prior to test trials enable the re-scaling of the readings collected during testing to a percentage reference value, unique for each subject within the study. This permits comparisons between both subjects and performances. Konrad (2005) details specific exercises to be performed in order to acquire maximal voluntary contraction values for individual muscles.

During the data collection muscle activation data was collected and stored using a Bio-Vision EMG system. Disposable snap electrodes, were positioned in pairs over the belly of the muscle, perpendicular to the direction of the muscle fibres. Signal amplifiers with attached gain switches which took the reading from the electrode to the control box were then connected to the electrodes. The control box was attached to a mini PC which was loaded with appropriate software with which to examine and record the muscle signal. It was with the mini PC that the collection frequency of the EMG signal could be controlled.

One pre-test was carried out with the EMG system to ensure that the system could detect the square wave pulse used to synchronise the data to the Vicon displacement data. This was accomplished by attaching a single set of EMG electrode to the Rectus Femoris, activating the muscle group by asking the gymnast to contract the muscles, and during this contraction, sending out the square wave to the receiver attached to the EMG mini-computer.

One other test was required of the EMG system to ensure that during a handstand on the rings, the system would be able to identify if a muscle was activated during the handstand balance. This was as most of the muscles in the body would be activated and working during such a strength skill, but only the muscle activations working to maintain the balance were of interest. EMG was to be collected to establish which muscles were specifically recruited during the handstand on the rings. It was also to be considered which muscle groups worked the hardest during the controlling of the balance in different situations. The main muscles of the human body are detailed in Figure 4.23 below.

In order to establish this the EMG were be positioned at pre-determined locations on the body, and data was taken during a balance. This trial was also performed during the pilot study, detailed in Section 4.2.3.

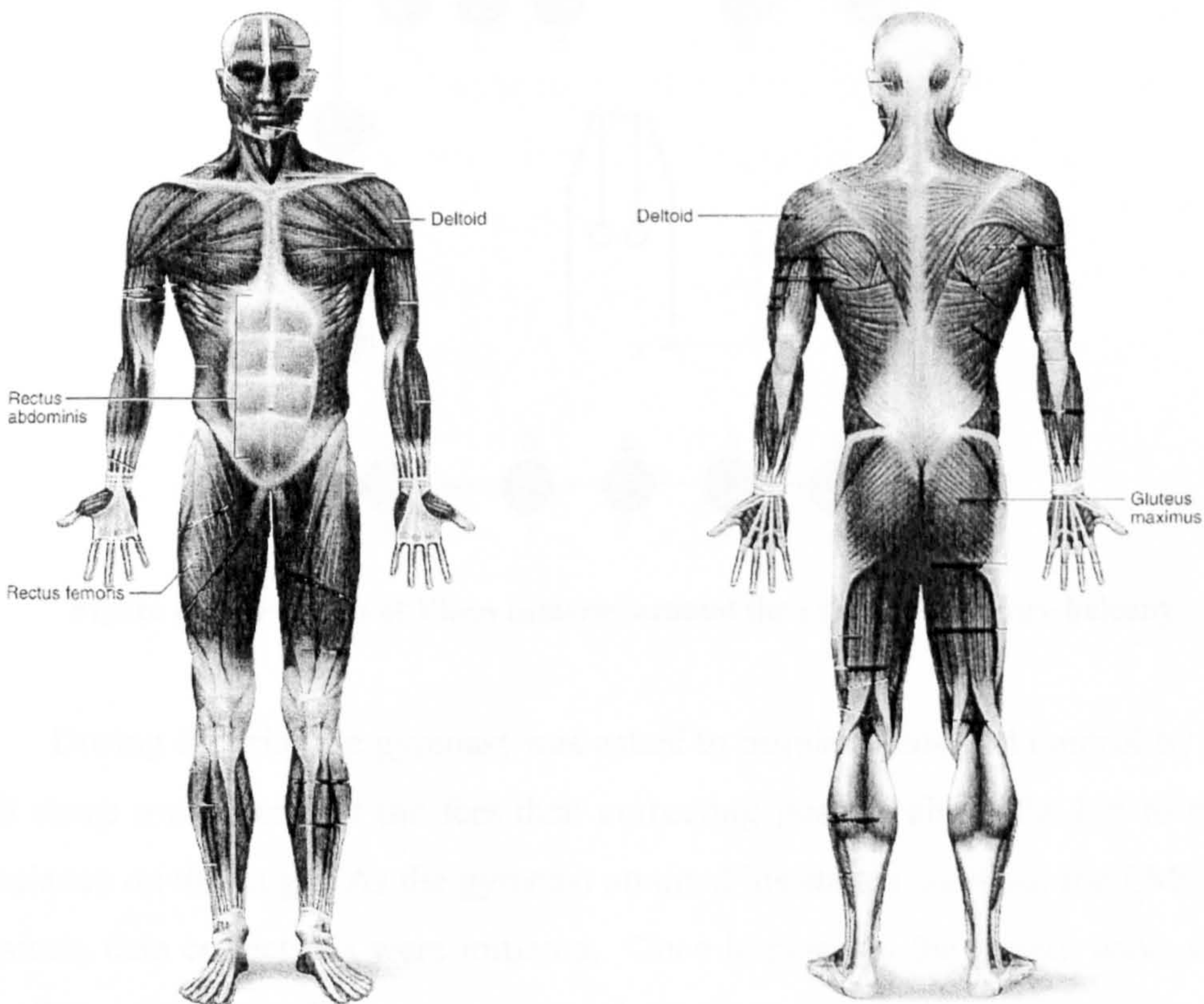


Figure 4-23: The anterior and posterior view of the superficial skeletal muscles, (adapted from Shier et al., 2004).

4.2.3 Pilot study

Before any data was obtained, informed consent was obtained from all participant gymnasts. The data collection took place in the Gymnastics Centre at Loughborough University. EMG, load cell and Vicon data were all collected during

the pilot study. However normal erect standing on the rings was used to represent an inverted handstand balance due to the necessity for multiple trials.

The senior male gymnast (gymnast C) wore a black T-shirt and black running shorts. The Vicon system was set up to use 18 cameras, with a data collection rate of 100Hz, the analogue input from Vicon was pre-set to 1000Hz, the load cell data was collected at 100Hz, and the EMG was also set up to collect at 100Hz for ease of synchronisation. The positioning of the cameras around the gymnastics centre can be seen in Figure 4.24.

EMG electrodes were placed in pairs on gymnast C, on the Rectus Femoris, Gluteus Maximus, and on the Rectus Abdominus. A single-pulse generator was used to send a square wave signal to the EMG mini-computer, the load cell PC, and the Vicon system.

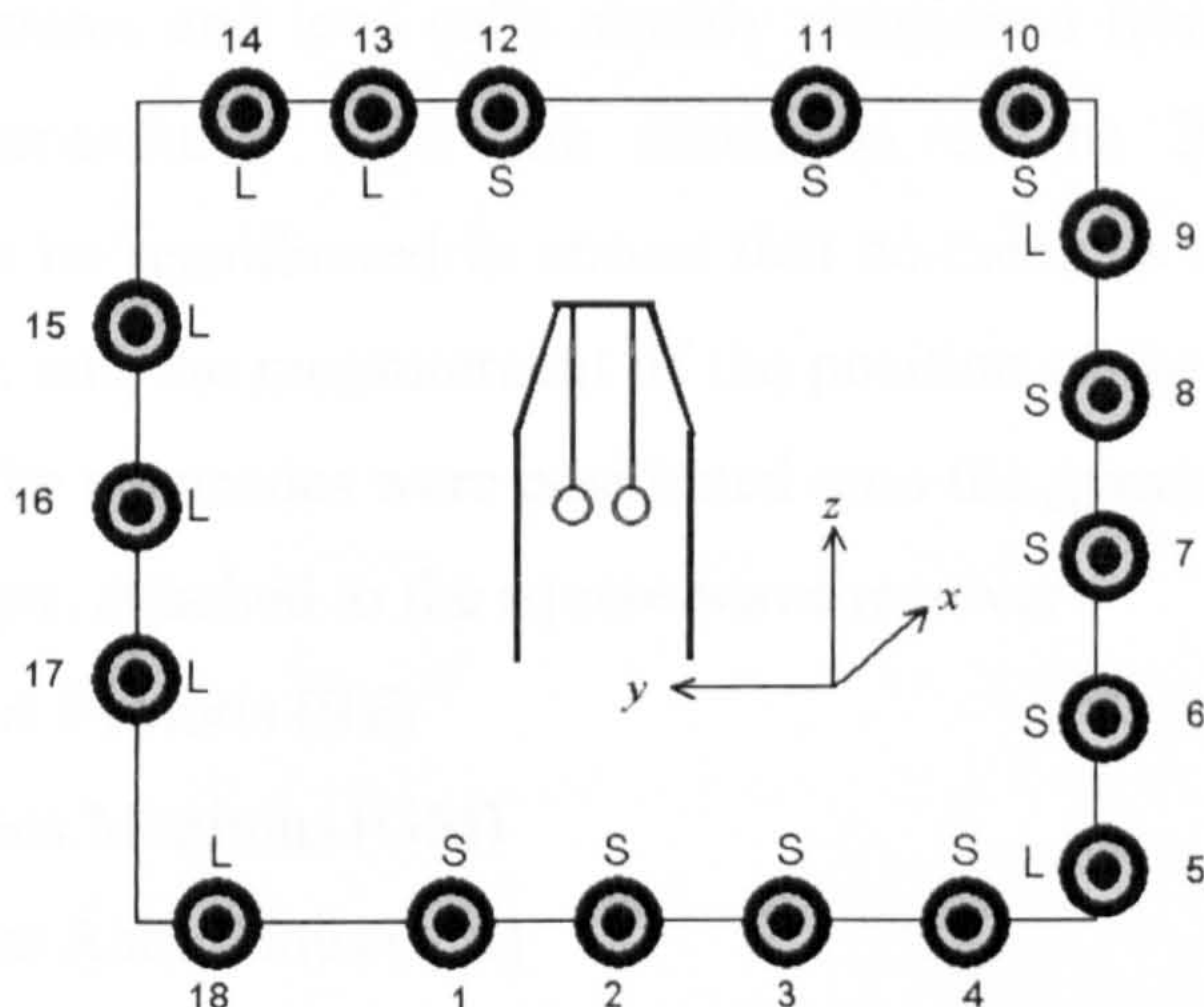


Figure 4-24: Position of Vicon cameras around the gymnastics centre balcony.

During the trial the gymnast was asked to mimic handstand control by making small sharp movements at the feet then correcting posture about the hip to maintain the balance on the rings. As the gymnast attained his stance position, the EMG, Vicon and strain data collections were initiated. Once in position the square wave was sent to the three receivers. This was repeated three times during the single trial in order to gain a choice of synchronisation points.

During the trial all three data sets were successfully collected, recorded, and synchronised. The Vicon cameras did not have any problems tracking the markers and produced an accurate reconstruction of the trial. The load cells detected force changes produced by the gymnast, and the variations in loading were sufficient to obtain a correlation between the strain reading and the displacement of the rings. The

EMG electrodes detected muscle activation, and when graphed had peaks which corresponded with the controlling movements produced by the gymnast.

4.2.4 Rings data collection

Anthropometric Data

For the main study, a senior elite male gymnast (gymnast S) performed the handstands on the rings. Before any testing data could be collected, anthropometric data was first collected on gymnast S. The measurements taken were in accordance with the model detailed in Yeadon (1990b).

Main Data Collection Methodology

With the cameras and load cells already positioned from the pilot study, the only outstanding procedures were: the allocation of the EMG electrodes; the collection volume to be recalibrated to ensure that no cameras had slipped or moved position in any way; and the measurement of the position of the rings with respect to the origin (0,0,0). The electrodes were positioned onto the gymnast S as follows:

- K1 - Trigger, attached to the square wave receiver
- K2 - Rectus Femoris (RF)
- K3 - Gluteus Maximus (GM)
- K4 - Rectus Abdominus (RA)
- K5 - Anterior Deltoid (AD)
- K6 - Medial Deltoid (MD)
- K7 - Posterior Deltoid (PD)

An earth electrode was also attached to the gymnast's patella, as an area of bony prominence. The gymnast was dressed in only black running shorts to permit the placement of the electrodes and of the retro-reflective body markers for the Vicon system (Figure 4.25).

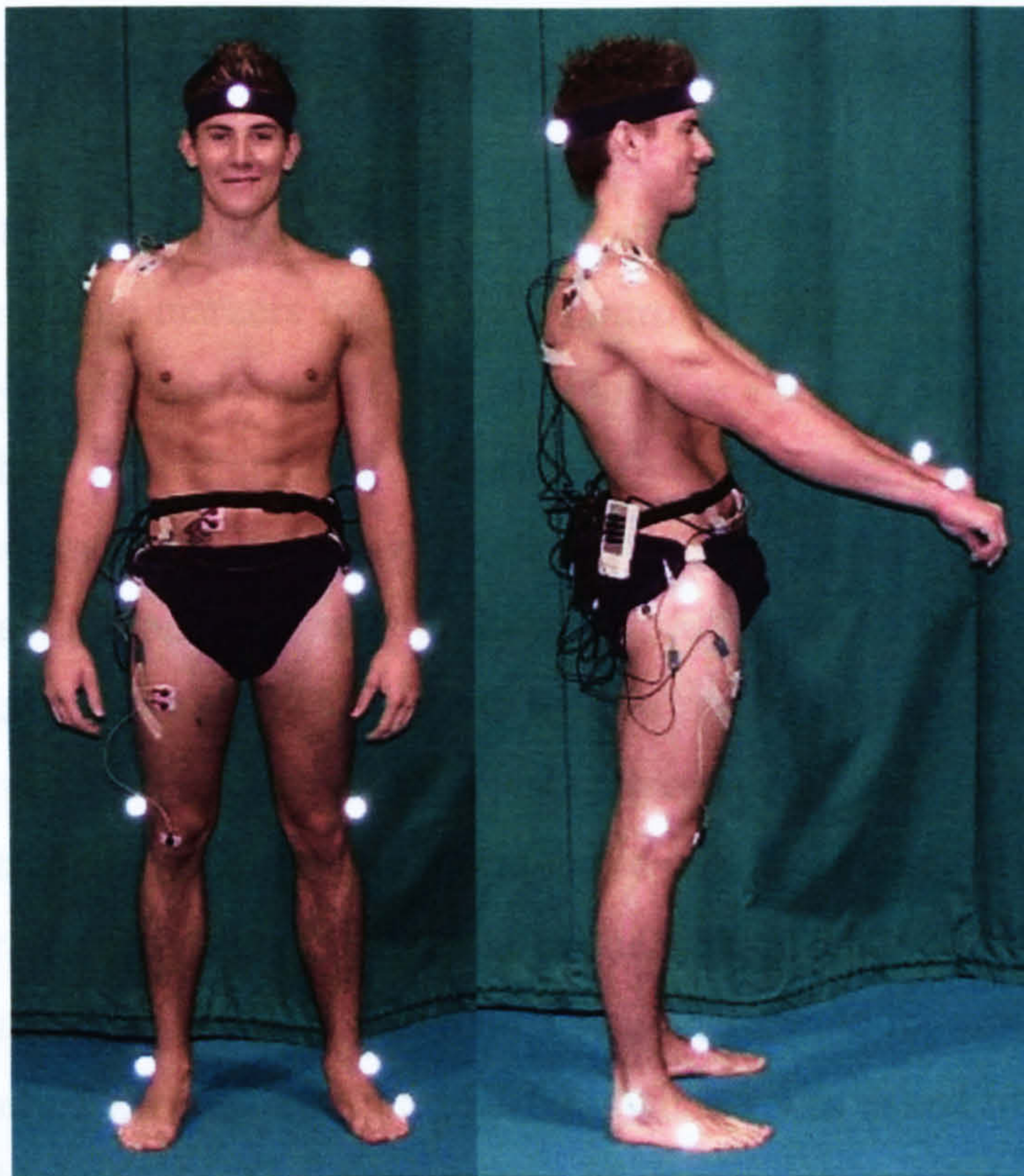


Figure 4-25: Gymnast S with EMG electrodes and Vicon markers.

Three calibrations were performed, and the best was saved and used for the data collection, with a mean residual of 1.5mm, and a residual range of 1.1mm (1.0 - 2.1). Only two cameras had a residual over 2mm, none over 2.1mm, and nine of the cameras had a residual below 1.3mm. The load cells at the top of the rings cables were recalibrated, and zeroed with a mass of 35kg. If the inertia and accelerations of the cables were of interest then the load cells would need to be as close to the rings as possible. The only output required from the load cells however was the cable tensions produced during the gymnast movements, which would be directly related to the strain reading produced by the load cells. As the strain would always act straight down the cable, the position of the load cells relative to the rings was not a consideration.

The co-ordinates of the centre of the two rings was found by dropping a plumb line down from each ring to the platform upon which the static calibration frame would be positioned. Each individual ring centre was marked, then measuring half way between them located the centre point. Measurements were then taken from that point back to the origin of the static calibration frame, positioned to the front-right of the rings. This gave the exact (x,y) co-ordinates of the centre of the two rings. As stated previously, the z coordinates provided no useful information for the study, as

the cable length was known, and so it was not necessary to obtain the z coordinate-origin.

During the data collection five trials were completed. The first was just a static trial of the cable markers for use as a control. This would allow comparisons between the dynamic trials and static trial to alleviate any environmental noise captured from the surrounding during the trials. Gymnast S had a mass of 77.9kg with all of the markers and EMG equipment in place, and 76.7kg without.

The following four trials were all dynamic, during which gymnast S performed a single handstand per trial. These trials will be referred to as *trials 1 to 4*. The gymnast was given adequate time to fully rest between each trial.

During trials 1 and 2, gymnast S was asked to hold a static balanced handstand on the rings for approximately 20 seconds, to the best of his ability. During trials 3 and 4 the gymnast was asked again to hold a static handstand for around 20 seconds, but approximately 5 seconds into the trial the gymnast was asked to close his eyes. Postural control is regulated by the integration of sensory information, of which vision is one of four main inputs: for adult gymnasts vision plays an important role in maintaining balance during difficult stances (Asseman et. al., 2005).

The gymnast was asked to close his eyes during the last two trials in order to prevent him from using vision to correct his balance, hence making him attempt to maintain balance with reduced feedback and consequently the control of the balance became very poor. This scenario was used to simulate a novice gymnast attempting to maintain a handstand balance on the rings.

All data required was collected successfully: the analysis and results will be discussed in the following section.

4.3 Data analysis

In this section, the data collected during the five trials will be evaluated, and analysed. Relationships and trends will be described, and theories will be discussed. Force data will be discussed first, followed by displacement data, and finally EMG data.

4.3.1 Force data

The load cells were zeroed with respect to the body weight of gymnast S so that only data resulting from movement of the handstand would be collected. New calibration loading equations were also calculated for both of the load cells:

Right load cell: $y = -0.0196x - 0.5147$; $R^2 = 0.9975$; S.E = 0.250.

Left load cell: $y = -0.0192x - 0.8283$; $R^2 = 0.9983$; S.E = 0.067.

Force data for the performances was calculated from the measured strain data. Using the calibration equations established earlier in the chapter, the recorded data from the right and left load cells were converted into Newtons. The data was then corrected for the zero offset of the load cells which was measured before any performances took place.

The data was then passed through a high pass filter in order to remove the effects of the swing of the cables. The filter was designed so that it passed high frequency data, but attenuated frequencies lower than the cable pendulum swing frequency of 0.3Hz. This was achieved using a Fourier Series representation. The coefficients which were below the cut-off frequency were then changed to zero in order to remove the cable swing. The peak forces during the four performances were calculated (Table 4.2).

From this data, it appears that gymnast S produced more jerky movements with his left hand than his right. This may be due to his left shoulder being slightly weaker than his right, or he may have favoured his left side when controlling the handstand.

Table 4-2: Peak forces from the four handstand trials

Load cells	Force (N)
Handstand 1 (R)	414.1
Handstand 1 (L)	406.4
Handstand 2 (R)	297.9
Handstand 2 (L)	516.7
Handstand 3 (R)	402.8
Handstand 3 (L)	537.9
Handstand 4 (R)	248.5
Handstand 4 (L)	574.4

The highest accumulative force, calculated by adding the right and left cable forces together for each trial, was observed during handstand 3.

A statistical analysis was performed to establish if there was a correlation between the displacement data and the force data. Using Pythagoras Theorem, the resultant 2-dimensional movement of each wrist was calculated. This distance was then correlated against the corresponding load cell reading by synchronising the data. The relationship was found to be significant at the 5% level for all four dynamic trials and for both the right and left wrists. It will therefore be expected that the largest movements were also measured during the third handstand trial. An example of the force data obtained can be seen in Figure 4.26 below.

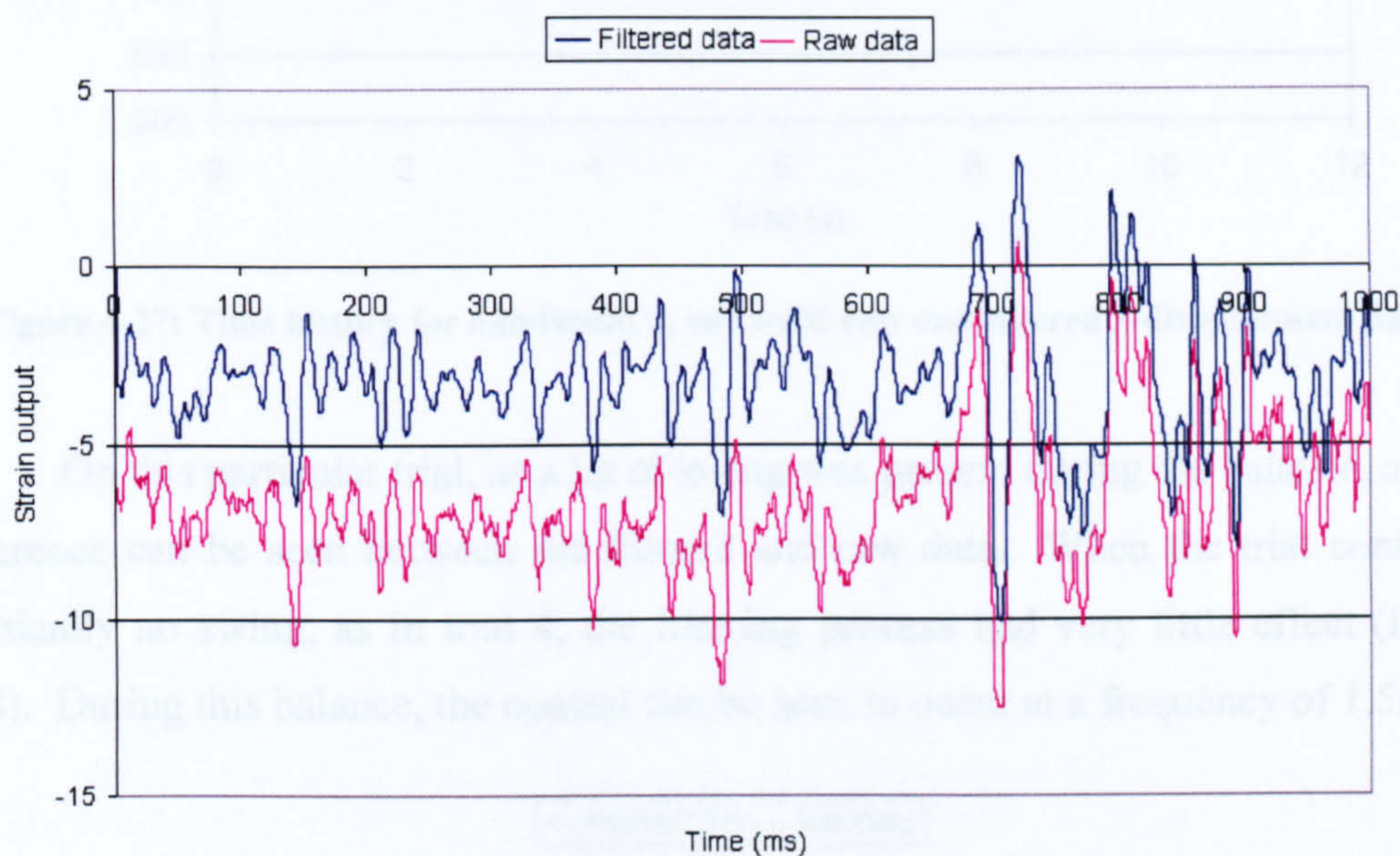


Figure 4-26: Time history for handstand 3, left wrist raw and filtered strain data.

4.3.2 Displacement data

Displacement information was the most important data to be collected with respect to designing the training aid. This was because it was important to establish the performance parameters of a handstand on the rings. Magnitudes of travel of the hands in both the x (forward and backward) and y (sideways) directions were necessary in order for the design to provide sufficient available movement for a novice gymnast to control a handstand properly without interference.

The displacement information was obtained by outputting the Vicon data as an ASCII file into Microsoft Excel. The data was then filtered like the strain data, using the same method as described above in Section 4.3.1. The effect of this filtering can be seen in Figure 4.27 below, which is taken from trial 3, during which the gymnast had significant swing. The swing was calculated to be at 0.3Hz, the remaining (filtered data) 2.0Hz is the movement the gymnast makes during the balance control.

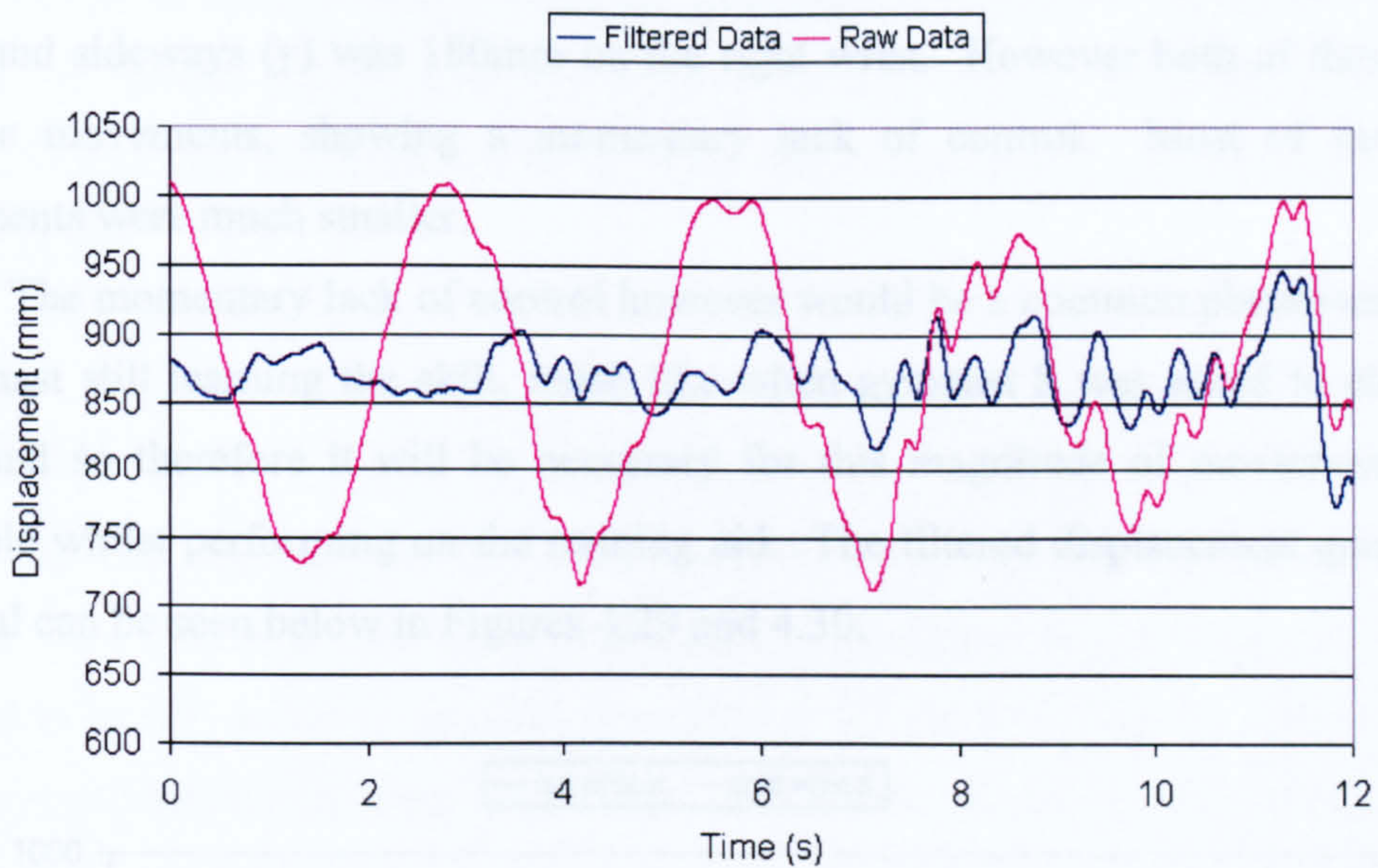


Figure 4-27: Time history for handstand 3, left wrist raw and filtered x-displacement data.

On this particular trial, as a lot of swing was present during the balance, a large difference can be seen between the filtered and raw data. When the trial contained practically no swing, as in trial 4, the filtering process had very little effect (Figure 4.28). During this balance, the control can be seen to occur at a frequency of 1.5Hz.

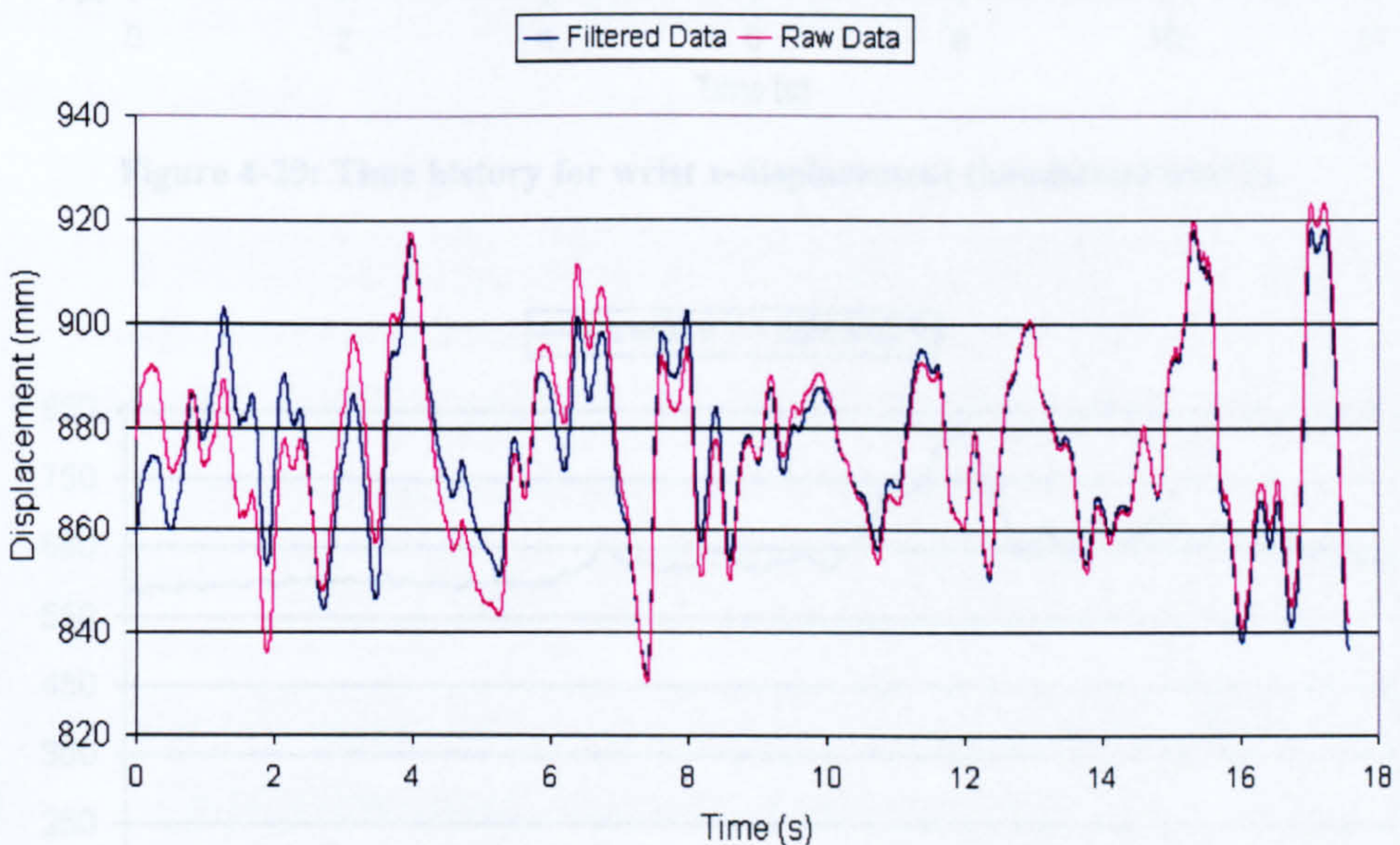


Figure 4-28: Time history for handstand 4, raw and filtered x-displacement data.

With the Vicon displacement data filtered, the maximum displacements were seen in the third handstand trial, during which approximately five seconds into the trial the gymnast was asked to shut his eyes for the first time.

The maximum displacement back and forth (x) was 244mm with the right wrist, and sideways (y) was 180mm on the right wrist. However both of these were extreme movements, showing a momentary lack of control. Most of the other movements were much smaller.

The momentary lack of control however would be a common phenomenon for a gymnast still learning the skill, much like when gymnast S was asked to close his eyes, and so therefore it will be necessary for this magnitude of movement to be available whilst performing on the training aid. The filtered displacement graphs for this trial can be seen below in Figures 4.29 and 4.30.

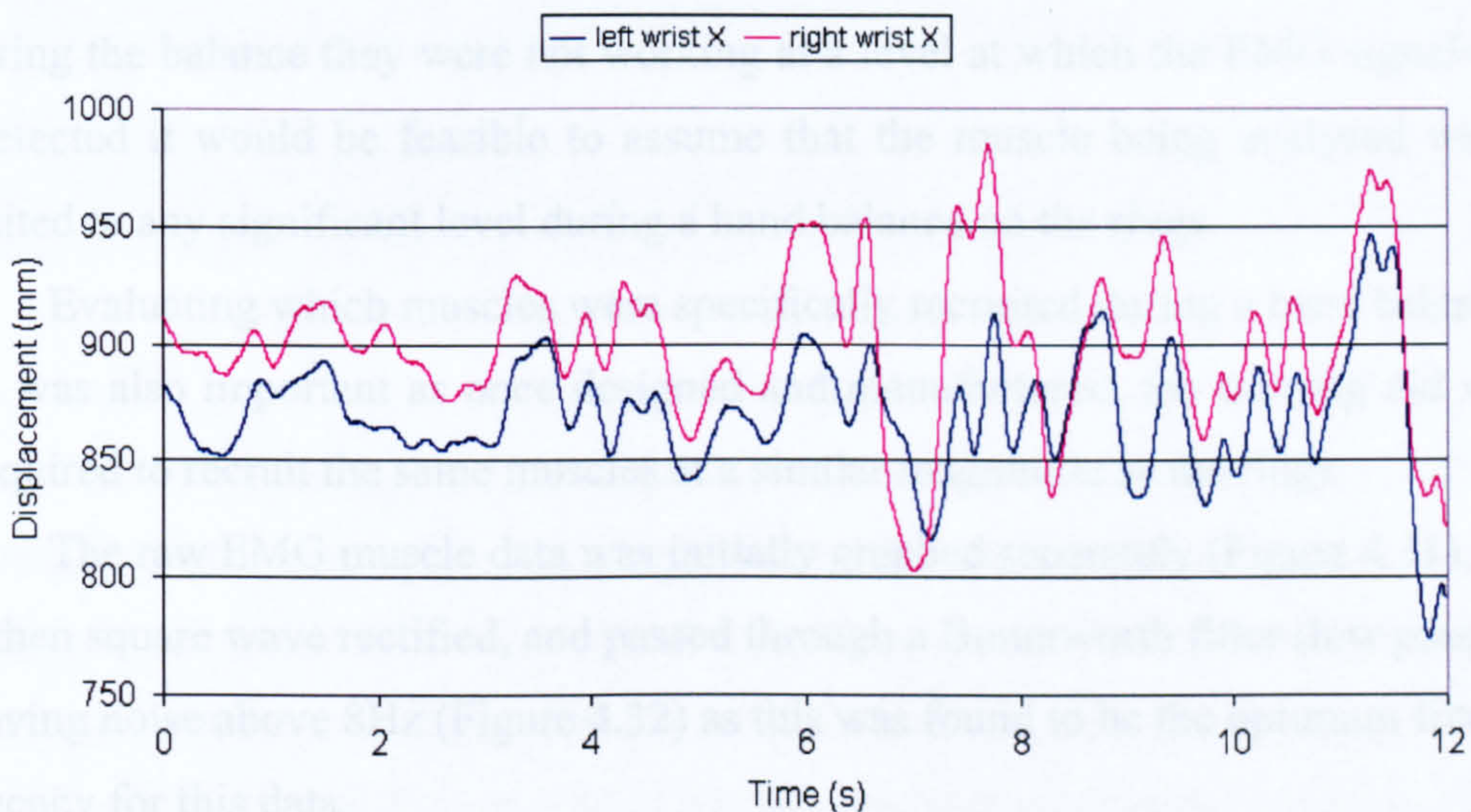


Figure 4-29: Time history for wrist x -displacement (handstand trial 3).

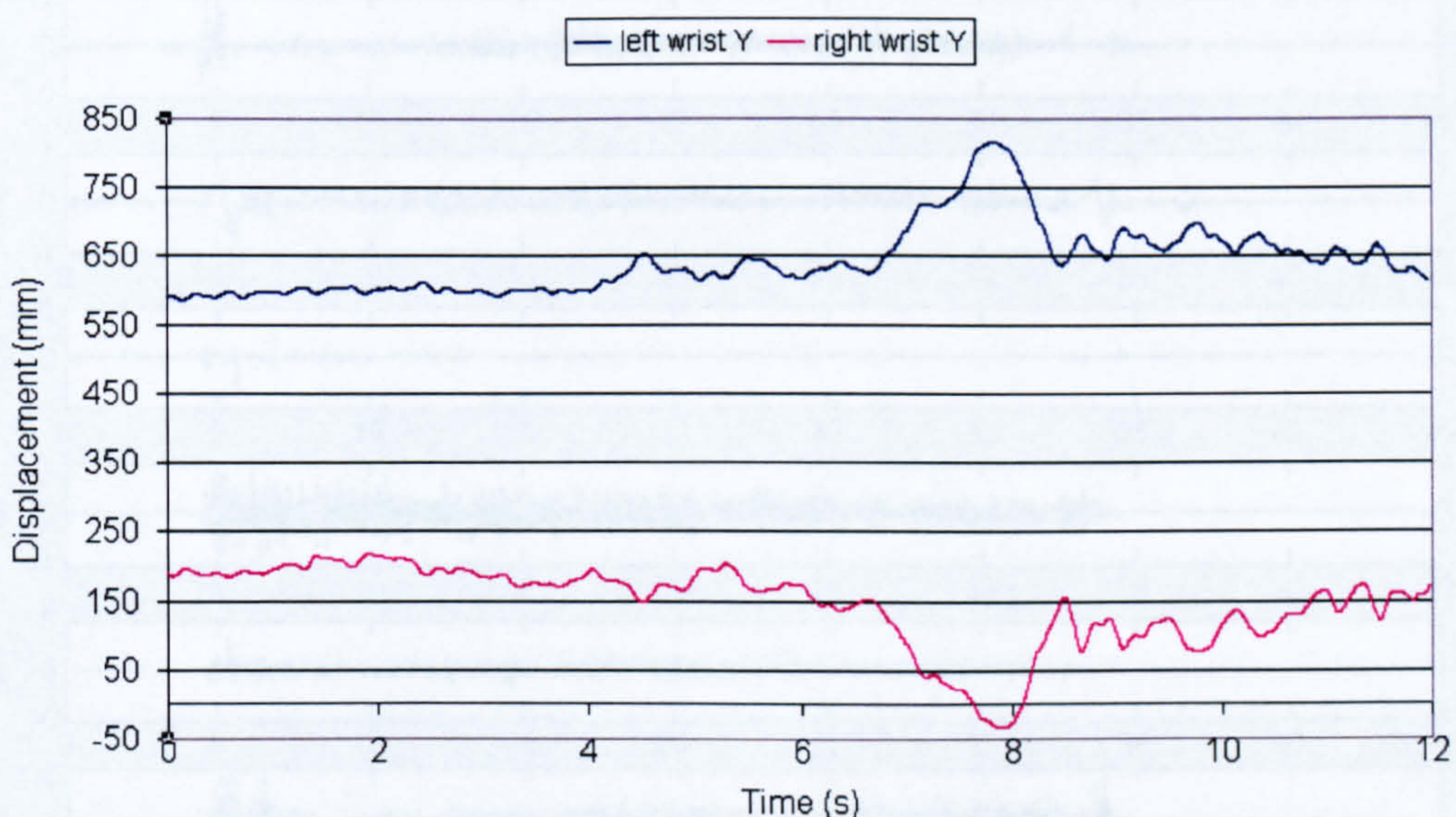


Figure 4-30: Time history for wrist y -displacement (handstand trial 3).

As can be seen on these graphs, the gymnast lost control of the balance around about seven seconds into the trial, just after he closed his eyes. Although he retained control, maintaining the balance with the eyes closed introduced a lot more movement into the skill.

4.3.3 EMG data

The main objective for the collection of the EMG data, was to establish which muscles were recruited during the control of a handstand on the rings. Muscles assumed to be active during the skill were chosen for the EMG signal collection, and if during the balance they were not working at a level at which the EMG signal could be detected it would be feasible to assume that the muscle being analysed was not recruited to any significant level during a hand balance on the rings.

Evaluating which muscles were specifically recruited during a hand balance on rings was also important as once designed and manufactured, the training aid would be required to recruit the same muscles at a similar magnitude as the rings.

The raw EMG muscle data was initially graphed separately (Figure 4.31), and was then square wave rectified, and passed through a Butterworth filter (low pass) removing noise above 8Hz (Figure 4.32) as this was found to be the optimum filtering frequency for this data.

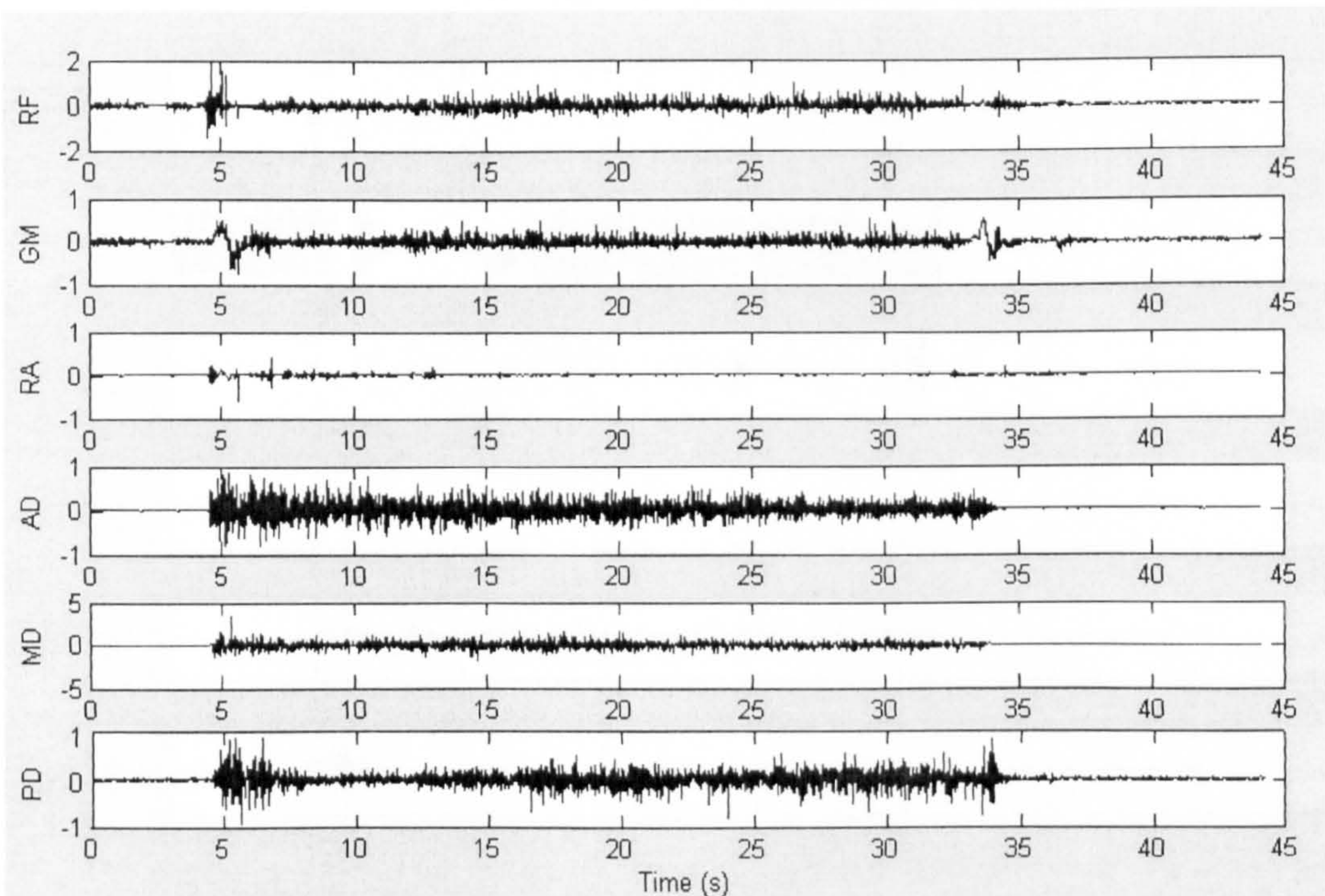


Figure 4-31: Raw EMG signal for handstand trial 2.

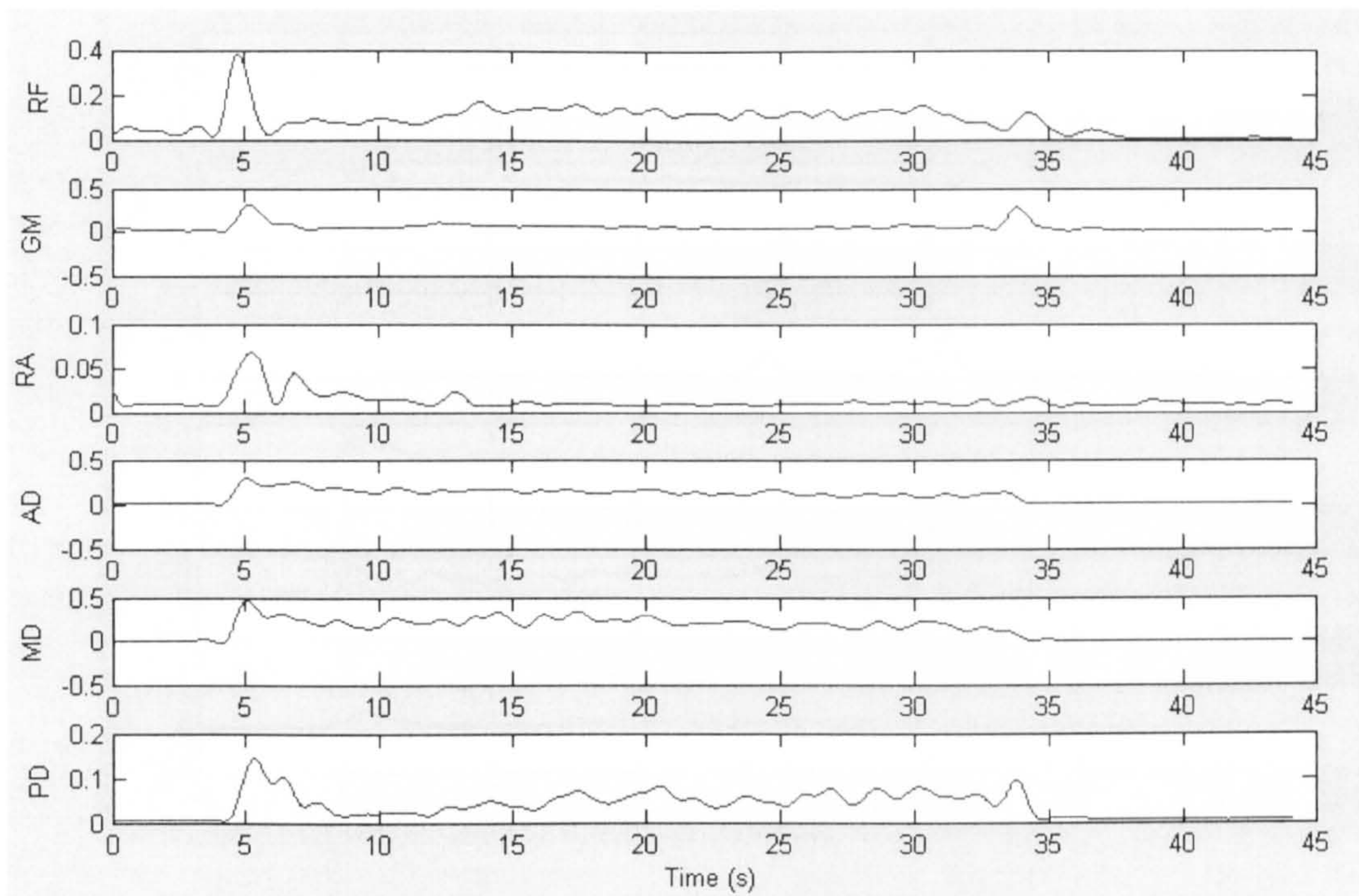


Figure 4-32: Processed EMG signal for handstand trial 2.

This EMG data gives very little information when considered alone without a maximal isometric contraction to compare the value to, however maximal isometric testing however was not necessary as the EMG was purely for comparison between muscles and trials, not to obtain absolute activation values.

Figure 4.33 and Figure 4.34 show the raw and processed EMG signal for a poor handstand.

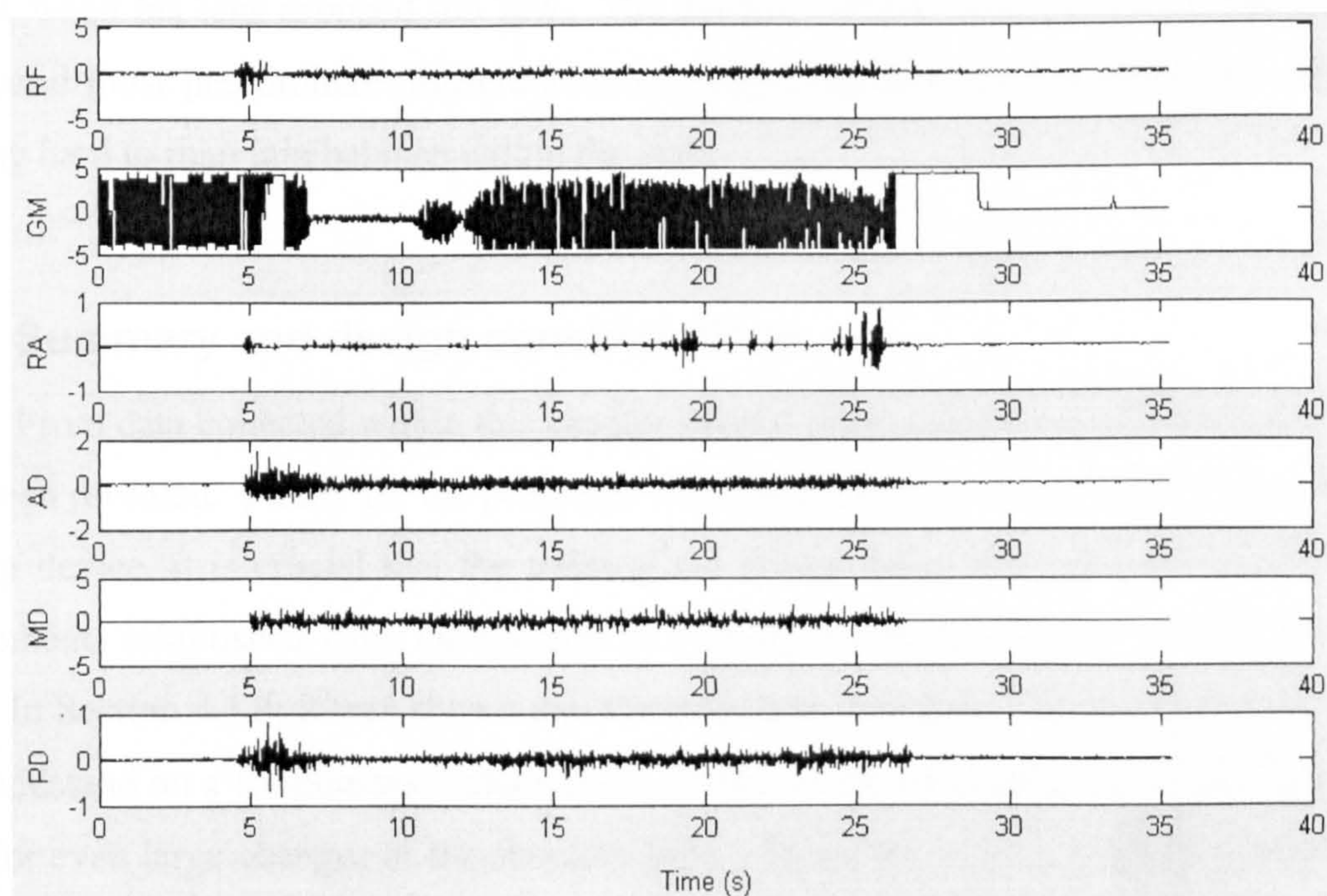


Figure 4-33: Raw EMG signal for handstand trial 4.

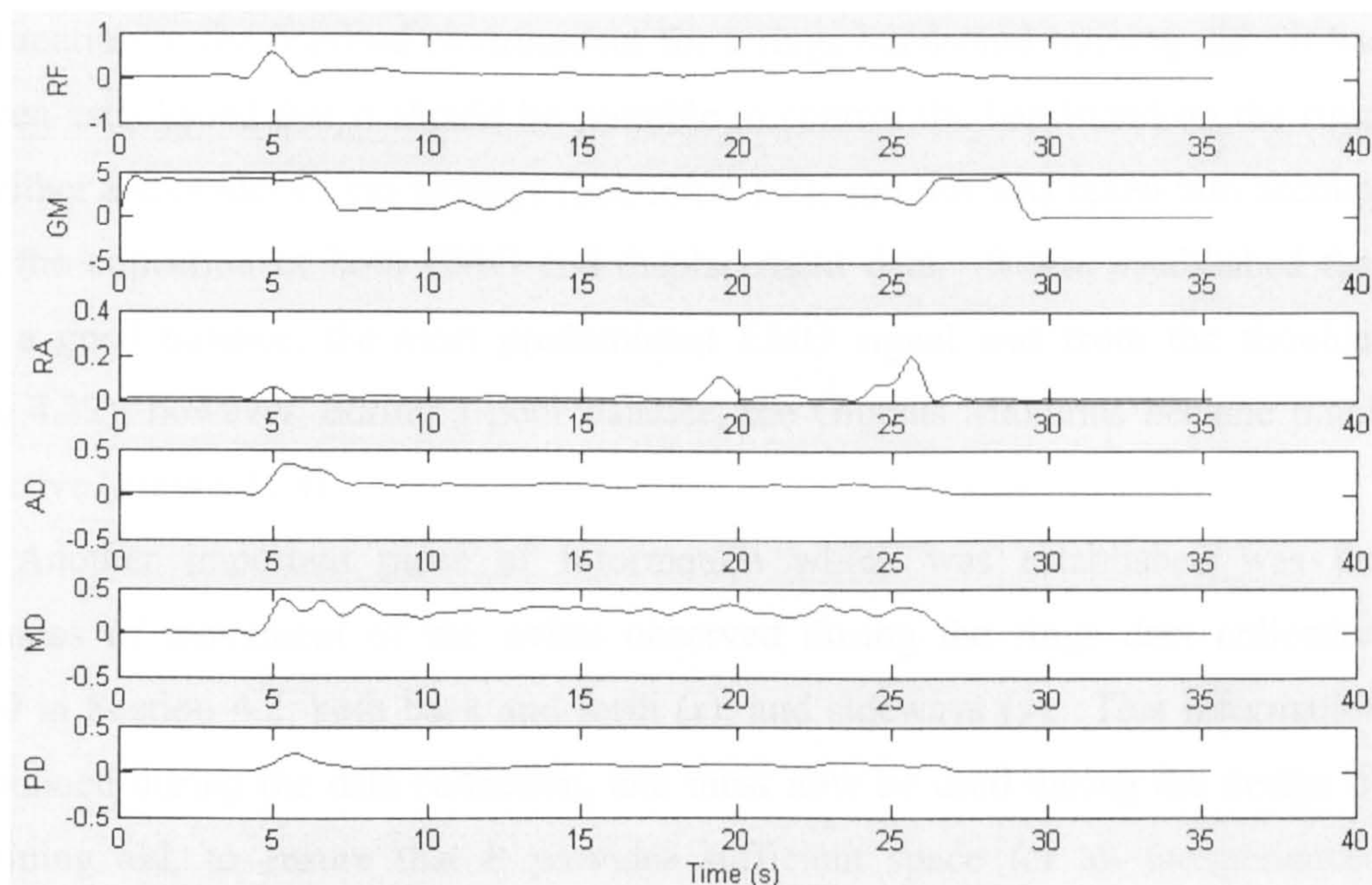


Figure 4-34: Processed EMG signal for handstand trial 4.

When comparing the two sets of EMG data for handstand 2 and handstand 4 a significant difference can be observed. The EMG electrodes were not altered in any way between trials, and so a comparison of the two graphs shows that during a good handstand the shoulders are slightly more active than during the poor performance, however during a poor handstand the signal from the Gluteus Maximus is much greater for a good performance. This suggests that the gymnast was either fighting hard to retain body shape during this time, or was using a hip strategy to control the balance when his legs dropped too low. The Medial Deltoid however still produces the second most predominant muscle activity, suggesting that the shoulders are still working hard to maintain balance within the skill.

4.3.4 Summary and design considerations

From data collected within this chapter several important pieces of information have been revealed. Firstly for the prototype training aid to be a valid rings handstand training device, it is crucial that the training aid design takes into consideration the requirements established from the theoretical training aid model in Section 4.1.2 and 4.1.3. In Section 4.1.3, it was shown that the calculated horizontal forces for a model of a handstand on a frictionless surface and a model on the rings differed by less than 1.3% for even large changes of the shoulder joint. Therefore as previously discussed, a flat frictionless surface rather than the curvature of the rings motion is an acceptable

approximation to the required environment for a rings handstand training aid. It has also been established that it should be possible to control the handstand on the rings using either a shoulder or hip strategy (Section 4.1.2), and this was taken into account during the collection of both EMG and displacement data. It was established that during a good balance, the most predominant EMG signal was from the shoulder (Figure 4.32); however, during a poor balance, the Gluteus Maximus became much more active (Figure 4.34).

Another important piece of information which was established was the magnitudes of movement of the wrists observed during the rings data collection detailed in Section 4.2, both back and forth (x), and sideways (y). This information was obtained during the data collection, and must now be used during the design of the training aid, to ensure that it provides sufficient space for an inexperienced gymnast to control a rings handstand. It is important that there is enough space available to the gymnast in which to control the balance without him reaching the limits of the training aid. The maximum distance travelled by the wrist in the sideways direction was during handstand 3 in which the wrist moved 180mm (Figure 4.30), and the minimum was during handstand 4 during which the wrist moved 85mm. The maximum distance travelled back and forth by the wrists was during handstand 3 (Figure 4.29) and the distance moved was 244mm. These dimensions must therefore be considered during the design development of the training aid which is detailed in the following chapter.

Finally the correlation between force and wrist movement was significant at the 5% level (Section 4.3.1), and the largest wrist movements correlated to the highest forces. The maximum total force of both wrists added together was calculated to be $940 \pm 0.25\text{N}$ (Table 4.2), and this was measured during the most unstable handstand (trial 3).

The following chapter will detail the design process of the rings handstand training aid, utilising the information established within this chapter.

5

Rings Handstand Training Aid Design and Manufacture

5.1 Introduction

In this chapter the design procedure undertaken during the development of the rings handstand training aid will be discussed in detail. Specific areas of the design such as the acquired data, and material specifications will also be reflected on.

Calculations, diagrams, and recommendations will be detailed in order to rationalize the choices made during the stages of the final design of the first training aid prototype. Full 3-dimension model diagrams of the training aid can be seen in Appendix A1.

5.2 Design path for a rings handstand training aid

The first stage in the design process once the design topic has been established, is to identify the crucial components of the design, in this case, a prototype training aid to help gymnasts learn a handstand on the rings. A design path is a mapped description of all of these amalgamated details. A generic gymnastics training aid design path was discussed in Chapter 3, and by making this design path specific to the rings handstand, a new design path has been developed. This has been achieved by collating all the information obtained from literature and from the data collected through initial testing detailed in Chapter 4. Information such as correct technique and required dimensions for the design of the training aid are all detailed within the design, which can be seen below (Figure 5.1).

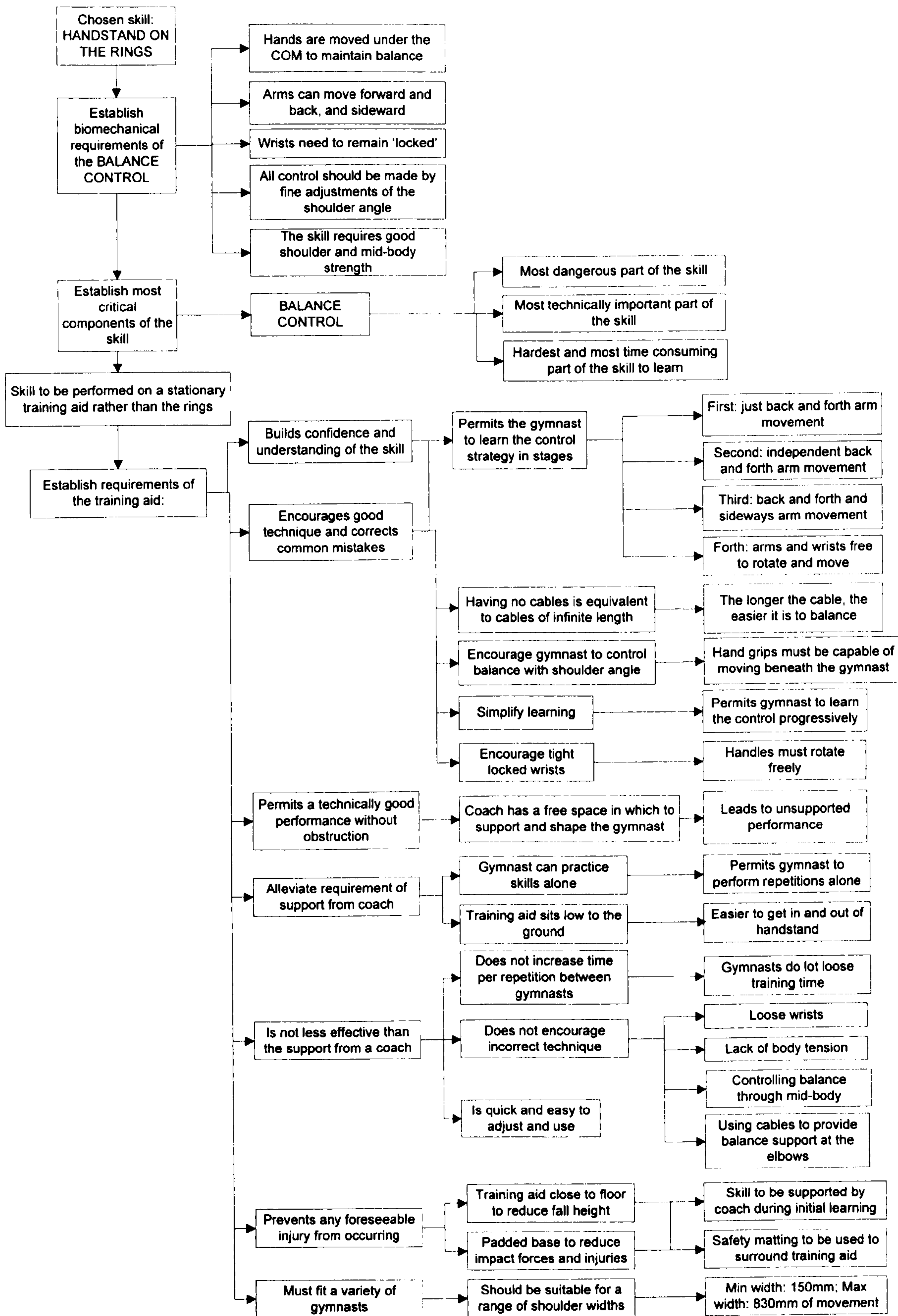


Figure 5-1: Design path for a training aid to help teach a handstand on the rings.

5.3 Requirement tree and product design specification

Collecting all of the information from the design path and from the initial customer requirement tree, it was possible to construct a detailed requirement tree (Appendix B1) and further to this produce a product design specification for the rings handstand training aid (Appendix C1). From the product design specification (PDS) it will be possible to develop a design that will fulfil all the required criteria of a training aid to help a gymnast learn a handstand on the rings.

Detailed within the PDS is information such as which British Standards the training aid is required to be tested against, information on the working temperatures of the training aid, ergonomic requirements, and performance and customer requirements. Both the detailed requirement tree and the PDS can be found in the Appendices.

5.4 Design process

This section will outline the process through which the innovative design was created. Relevant calculations and diagrams will be used to support the design decisions detailed within this section.

5.4.1 Design data from testing

As was stated in Section 4.3.4 in the previous chapter, there were four main values obtained from the data collection which are crucial for the design of the rings handstand training aid: the maximum distance travelled back and forth in x direction by the right and left wrist, and the maximum distance travelled sideways in the y direction by the right and left wrist. The single maximum value of travel back and forth was measured to be 245mm, and sideways was measured to be 180mm. Besides these two design dimensions, a minimum distance of travel for the wrists inwards (coming together sideways) must also be considered. This would be determined by anthropometric data, mainly concerning the average shoulder width of male gymnasts who would be likely to use the training aid. This information was obtained from Yeadon and Trewatha (2003), and provided minimum distance between shoulder joint centres of 230mm for a group of gymnasts of ages 16.5 ± 2.9 years, mass 52.4 ± 10.0 kg and of heights 1.61 ± 0.07 m.

5.4.2 Preliminary design concepts

As a training aid for a handstand on the rings must replicate the rings apparatus as closely as possible, several design constraints were immediately established. As previously discussed, the training aid must provide a frictionless environment in which the gymnast may control the hand balance, and the arms must be able to move independently, forwards, backwards and sideways, requiring at least two surfaces upon which the balance will be held. On the rings, the arms can also rotate longitudinally about the length of the arm, so this degree of freedom must also be considered. With this as an initial challenge, conceptual ideas were minimal. An idea generation process took place, and possible modes of movement considered were:

- **Wheels:** Smooth fluid motion, minimal frictional forces involved. However do need tracks to guide the motion of travel, and can be complicated to build around. Also it would be hard to 'fix' to the floor without preventing motion.
- **Linear bearings:** The slider block is designed to be built around the rails which are attached to a base, and the rails can be stopped easily by end stopper blocks.
- **Ball bearings:** Would require tracks the same as the wheels, but would provide a smooth frictionless motion and would be possible to build around.
- **Two opposing frictionless surfaces which would slide over each other:** for example Teflon. This concept however may not be feasible in terms of producing a training aid.

5.4.3 Analysing conceptual work

Morphology Charts

Wright (1998) explains that a morphology is concerned with the study of the structure or form of things. Designers use a morphology chart to consider all of the different ways that the functional requirements of the design problem can be fulfilled. The chart is a graphical representation of the possible solutions to the functional requirements. As the components of movement were the main processes to be considered in this design, a morphology chart was developed to enable the consideration of possible designs (see Figure 5.2):

Morphology chart:

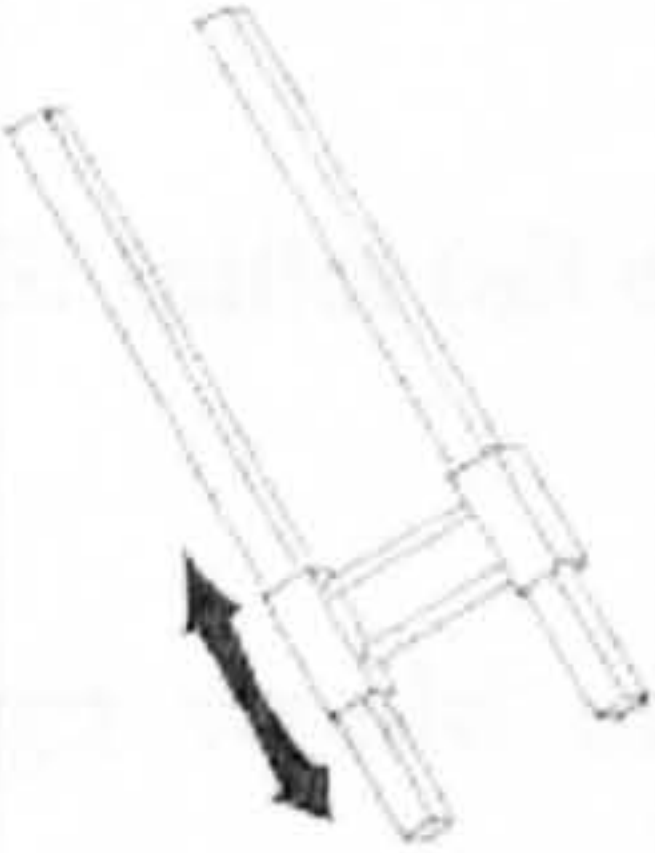


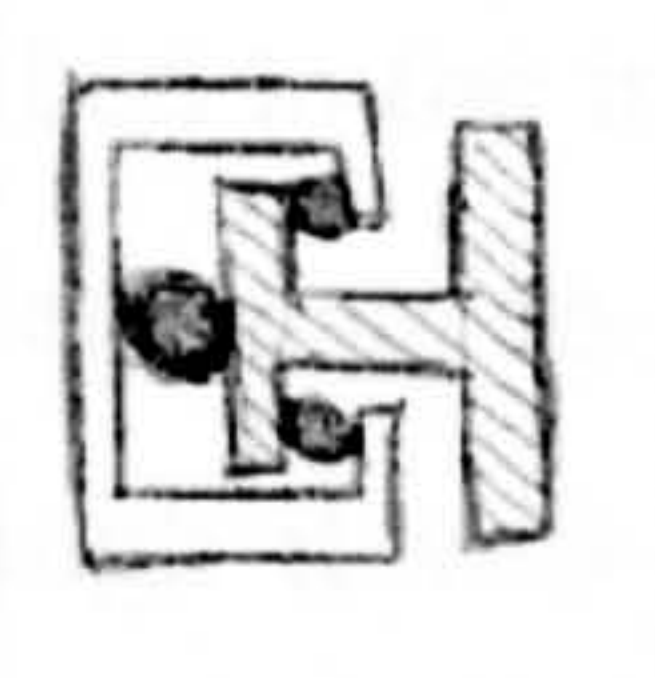
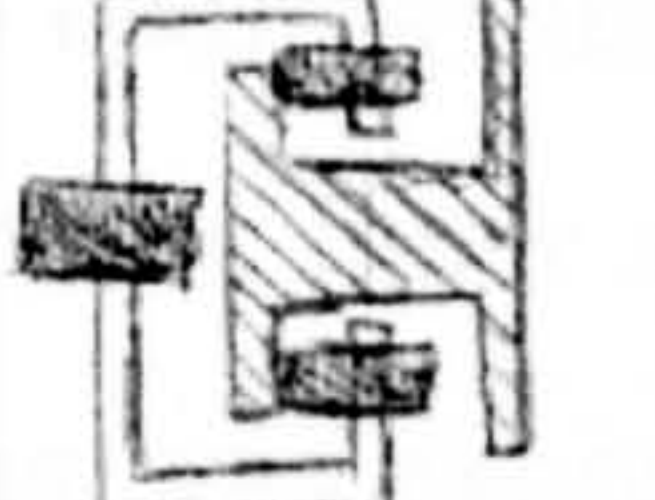

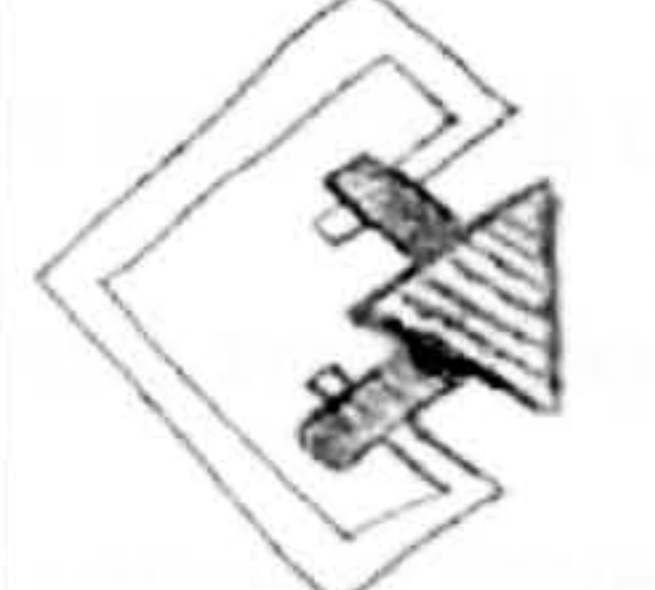
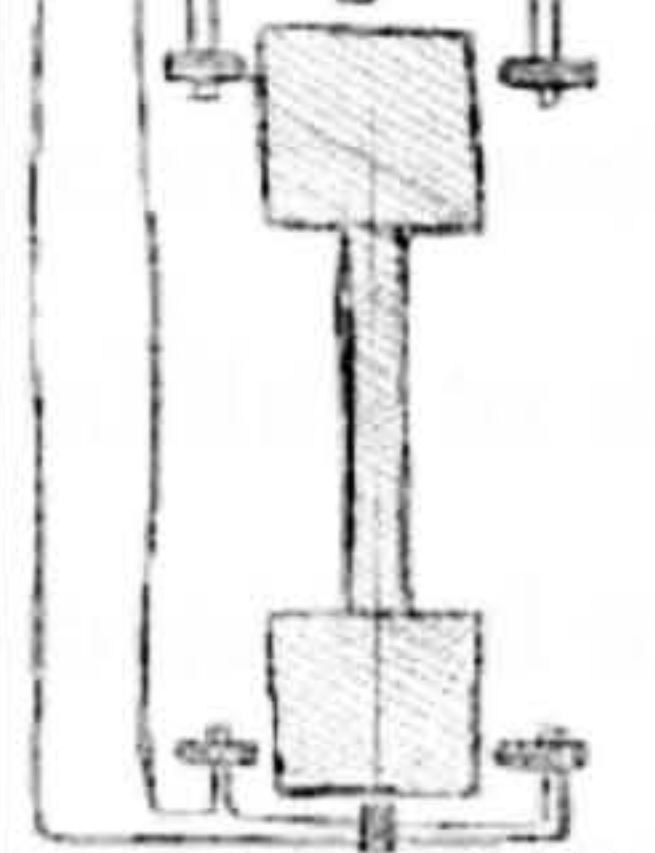
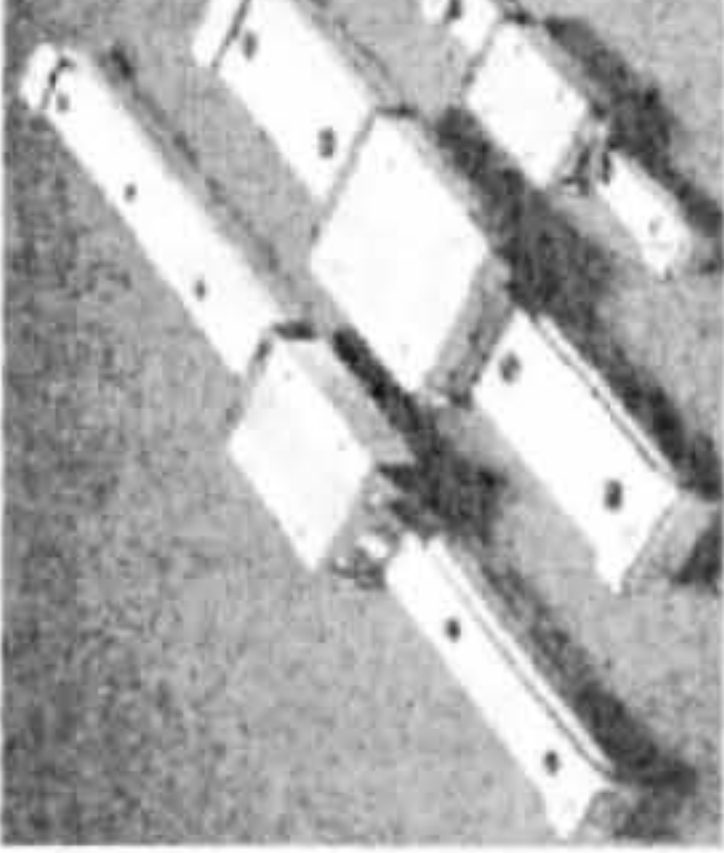
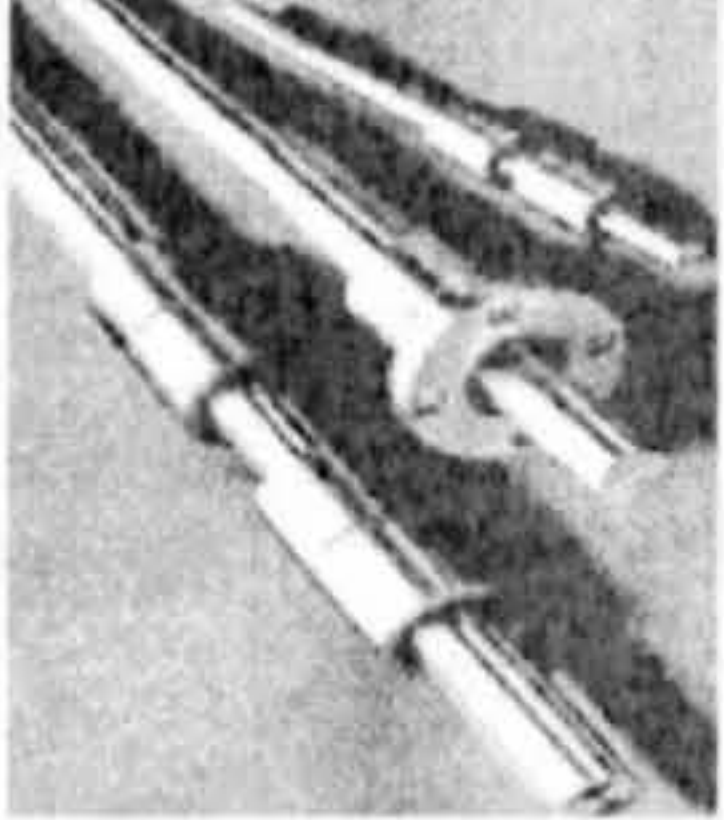






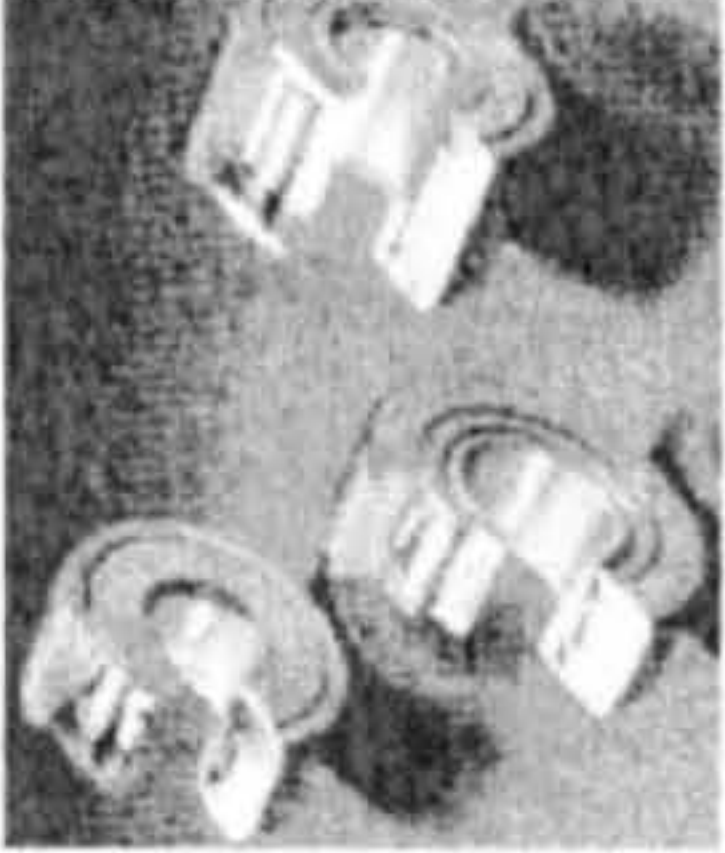








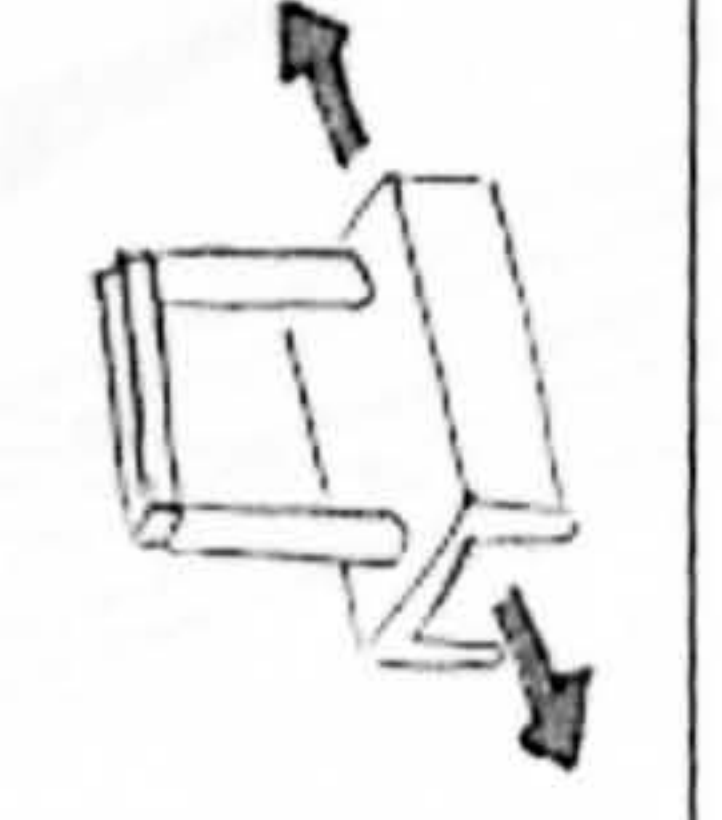
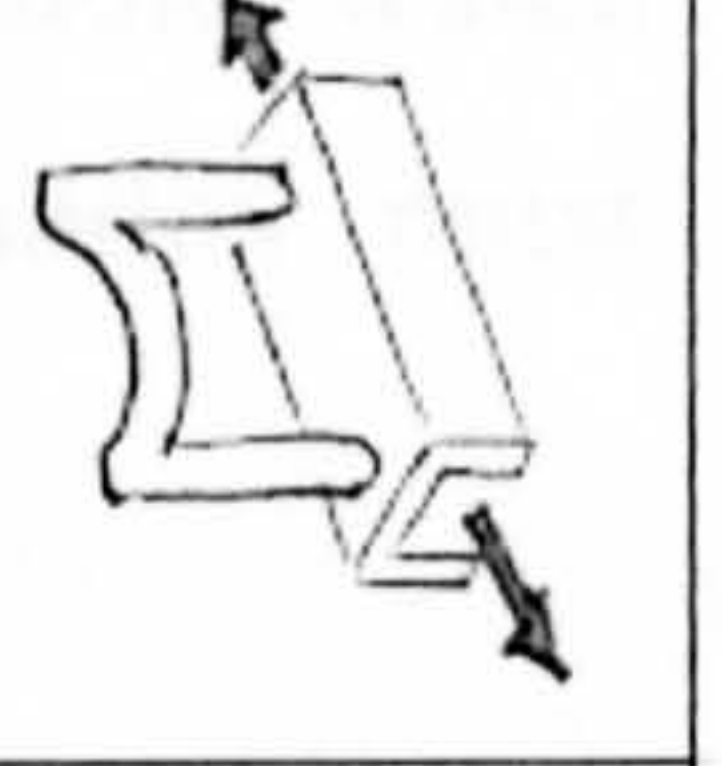
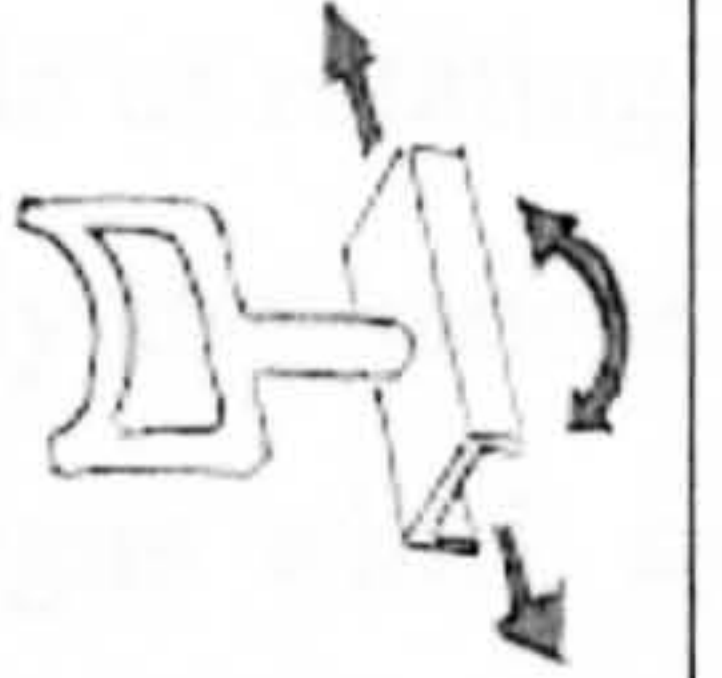



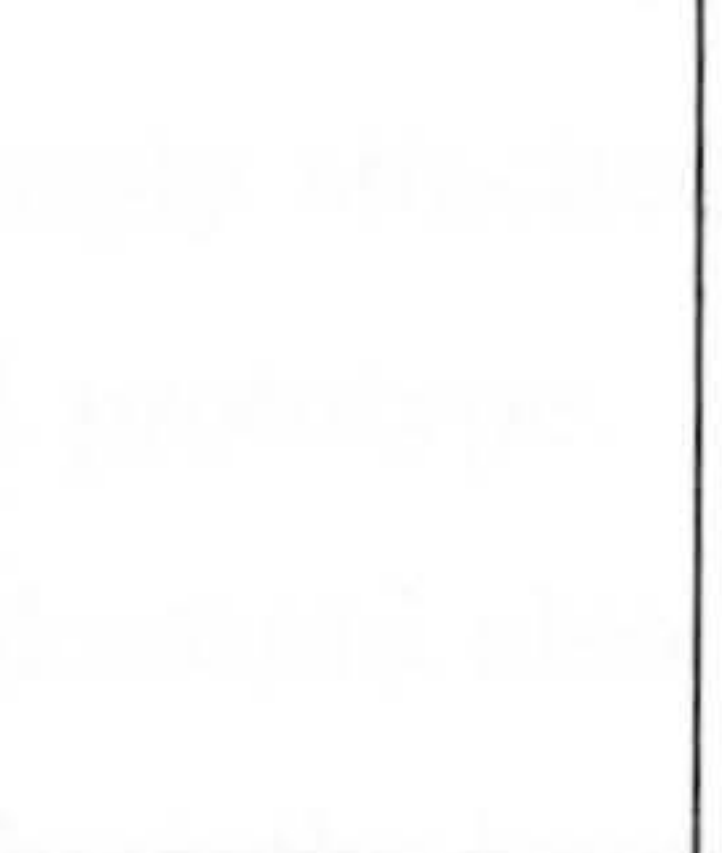
A	Forward and backward motion								
B	Sideways motion								
C	Rotational motion								
D	Handle design								

Figure 5-2: Morphology chart for the rings handstand training aid (not to scale).

Through the use of the morphology chart, and by considering the requirements outlined in the PDS, a concept design was chosen (Figure 5.3). It was established that the design would use flat linear rails as in A1 as they were the most simple solution. As the rails (A1) were also linear they could be rigidly and simply attached to a solid flat base, providing stability to the structure of the training aid prototype. It was decided that round rails would lead to more complicated fixing, and would also require further adaptation to prevent the blocks on the rails from rotating about the longitudinal axis of the rail. The other solutions detailed in row A of the morphology chart were all of more complex design and were not considered to give significantly better results. The rails (A1) permitted a second layer to be built on top of them as they had a flat top surface unlike A2, A5, A6 and A7, and were much lower to the ground than A3, A4 or A8 with regards to the safety considerations of the training aid. For the same reasoning, the flat linear rails pictured in B1 were chosen to provide the sideways movement of the training aid. The bearings used to provide the handle rotation were those shown in C1. This was because the inner surface and outer surface would rotate separately, and no part of the bearing was exposed to the atmosphere. This component would permit the handle to be attached to the inner surface, and still be capable of rotating when the outer surface was also attached to the slide in some way. Finally the handle design chosen was D4, as although it was one of the tallest handle designs which might introduce some instabilities into the design, it was the only handle which would permit longitudinal rotation. When designing the handles, stability must be taken into consideration.

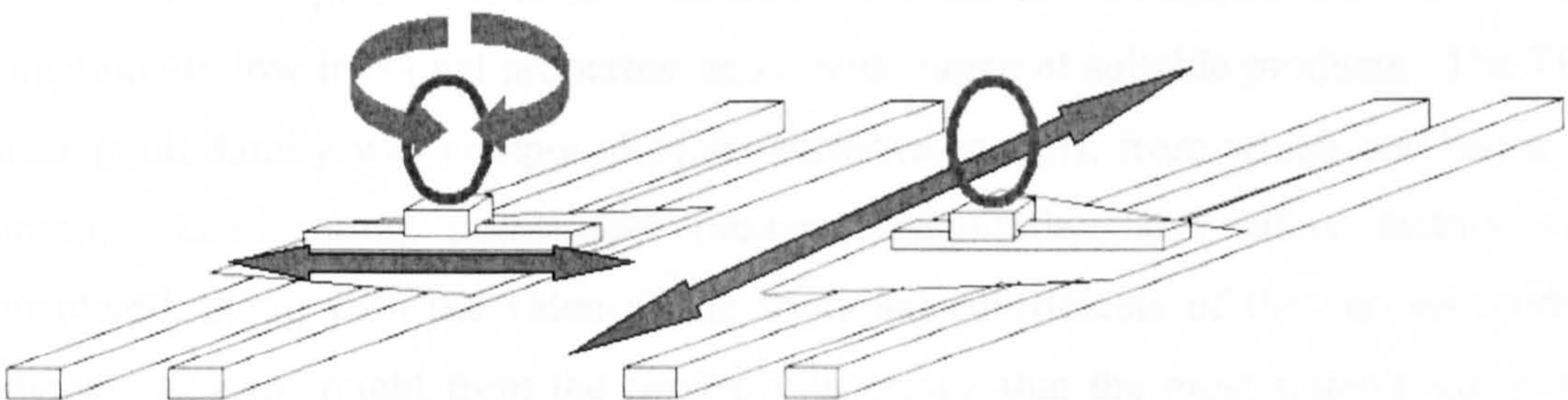


Figure 5-3: Initial full concept of the rings handstand training aid (not to scale).

This design would enable each arm to move with three different degrees of freedom. To conform to the PDS the training aid was supposed to simplify the learning of the rings handstand. To do this it was decided to strategically limit the movement available to the gymnast, incrementally increasing the movement degrees of freedom as the gymnast learned to control the balance.

From observations and interviews during the first data collection (detailed in Chapter 4), it was decided that the most prominent motion during the balance of a rings handstand was back and forth, so this was to be the first motion which the gymnast would learn to control. This would first be learnt with arms dependent of each other, moving together, and then secondly with the arms moving independently, once the gymnast was ready to advance. The third motion to be released would be the arm movement sideways. The final stage of motion would be to release the rotation at the wrists as this appeared to be the most complex movement to control. In the design, methods of restricting these movements must be established.

Before any final decisions could be made regarding the training aid, it was crucial that any required calculations to ascertain component specifications were performed. These will be detailed in the following section.

5.5 Design calculations

For the concept to become a feasible design, components had to be obtained. To ensure that the correct components were utilised within the design specific calculations were completed.

5.5.1 Linear guide specification

The linear guide was to be obtained from THK, as the components available had exceptionally low frictional properties and a wide range of suitable products. The THK linear guide family was composed of six different models, from which one had to be chosen. Load rating, permissible moment magnitudes, and safety factors were considered, along with the value of the frictional coefficients of the various models. Advice was also sought from the company to ensure that the most suitable guide was chosen.

Characteristics of the various models were carefully considered, and the final choice was to use the SHS-C Ultra-heavy-load model. This particular model was also a *four-way equal-load type*, which enabled the guide to be used in any direction as it was capable of bearing loads in all four directions: radial (P_R), reverse-radial (P_L), and two lateral directions (P_T) (Figure 5.4). This would permit the training aid to perform well under any loading situation imposed upon it by the gymnast.

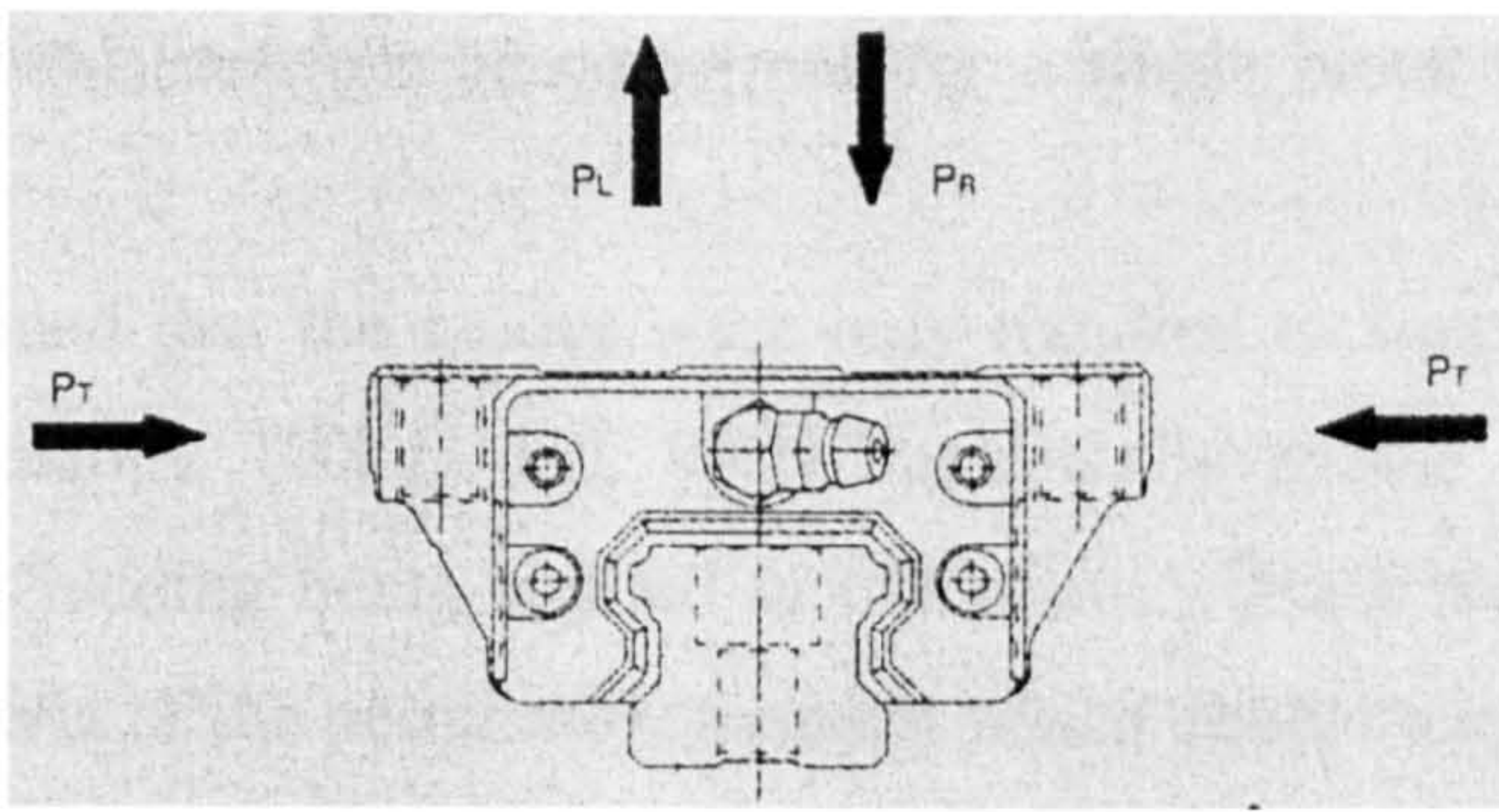


Figure 5-4: Type SHS linear guide loads (adapted from THK General catalogue).

The criteria for the rails were

- Enhanced grease retention for low maintenance.
- Low fluctuations in resistance to ensure smooth motion.
- High misalignment absorbency for the ease of production.
- High rigidity as large loads would be applied to the guides.

This model of linear guide was quoted to have a friction coefficient (μ) of 0.002-0.003, which decreased with increased imposed load rating (Figure 5.5).

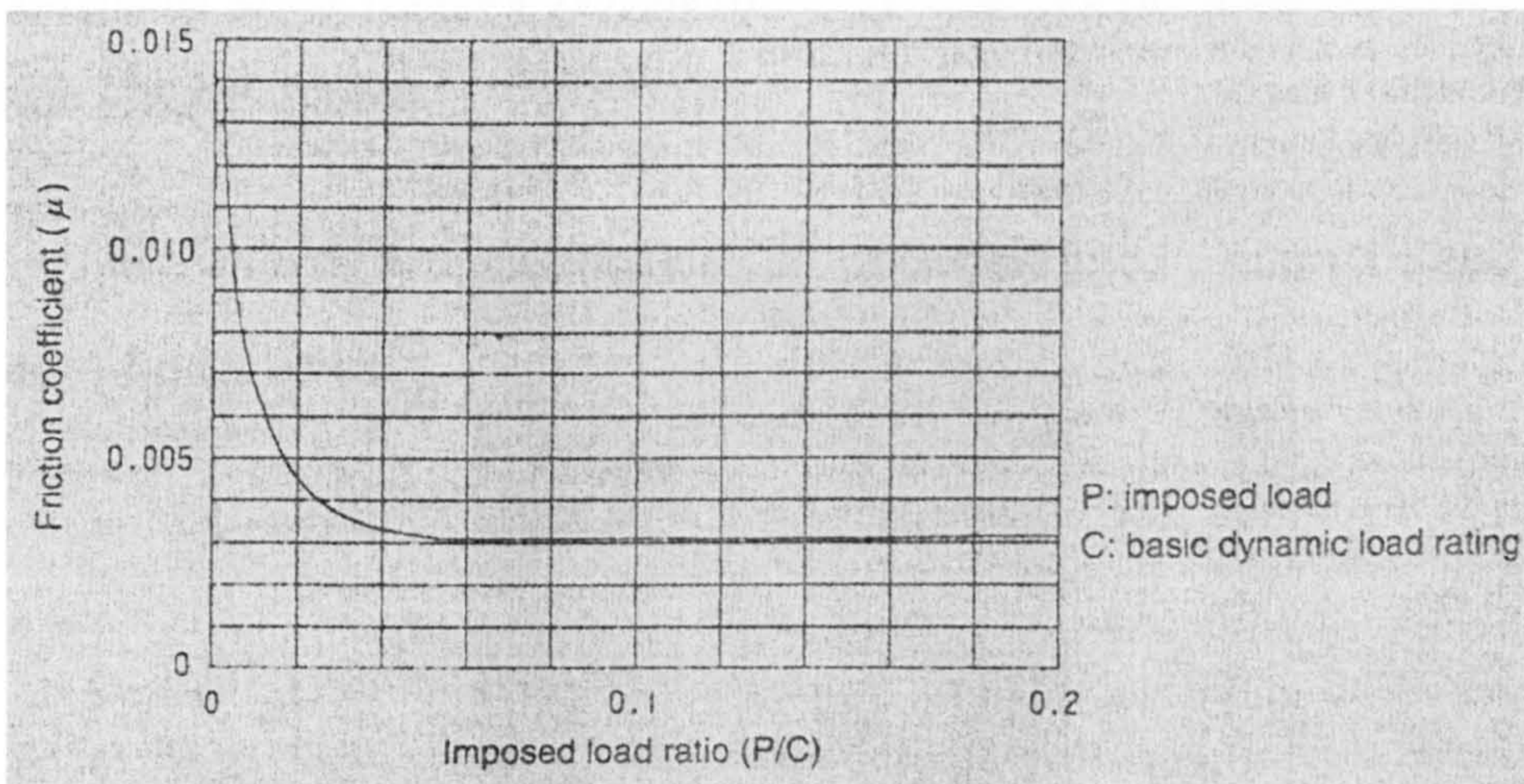


Figure 5-5: Relationship between imposed load ratio and friction coefficient (adapted form THK General catalogue).

5.5.2 Linear guide calculations

To obtain the standard dimensions of the linear guides to be used, the loading constraints needed first to be calculated to ensure the correct guides were chosen. As design dimensions had not yet been established, these calculations were approached from a worst case scenario to ensure that an adequate safety factor had been introduced.

All calculations would therefore be performed for a single block rather than multiple blocks.

It was assumed that the guides were only required to support loads of 1000N vertically (approximately 100kg), but 100N horizontally as the low friction would prevent almost any loading being applied in this plane. Using the dimensions of the blocks, and the criteria of the permissible moment which could be applied to the various blocks, a suitable choice was made. As this model was for *ultra-heavy loading*, the smallest of the blocks was suitable for this purpose.

As any loading would be applied to the top surface, the critical dimensions were the length of the block (64.4mm), the width of the block (47mm) and the over all height of the block (24mm). From these dimensions the loading moments could be calculated and compared to the permissible moments (Figure 5.6) for the smallest block:

Maximum $M_A = 1000N \times (64.4/2) \times 10^{-3} = 32.2Nm$ and the permissible moment M_A for a single block = 175Nm.

Maximum $M_B = 100N \times (64.4/2) \times 10^{-3} = 3.22Nm$ and the permissible moment M_B for a single block = 175Nm.

Maximum $M_C = 1000N \times (47/2) \times 10^{-3} = 23.5Nm$ and the permissible moment M_A for a single block = 160Nm.

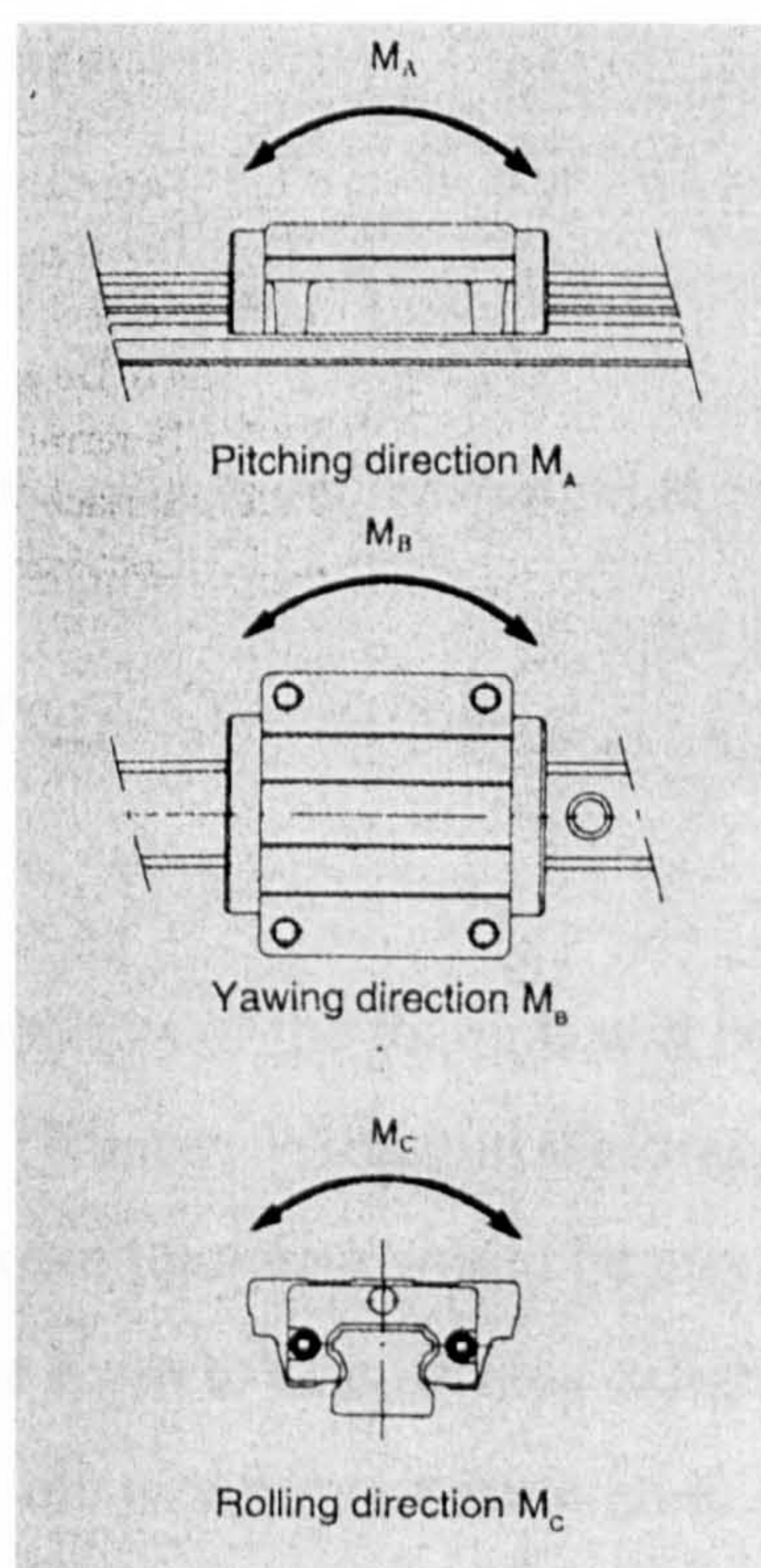


Figure 5-6: Permissible moments for THK slider blocks (adapted form THK General catalogue).

It was therefore determined that by using SHS 15C blocks there would be a significant safety margin introduced into the design. With the rail specification established it was now possible to identify the required dimensions of the training aid. However considering British Standards BS EN 913:1996, it is required that when gymnastics equipment is tested in accordance with the specified test methods, the peak acceleration of an 8kg mass dropped from a height of 1m must not exceed 500m/s^2 (50g). Therefore, the surface padding of the training aid was now considered.

5.5.3 Top foam calculations and testing

It was decided that the best material to cover the exposed areas of the training aid was foam. This was to provide adequate padding to prevent injury if the gymnast was to fall from handstand, and also for the equipment to be in accordance with the British Standards for gymnastics equipment. By initially considering the foam as a perfect linear spring, and assuming that there was constant acceleration, and therefore linear acceleration (so that the value of the peak force would be as low as possible), the required depression of the foam to produce maximum deceleration of 50g was calculated using Newton's equations of motion:

From a drop height of 1metre:

$$v^2 = u^2 + 2as$$

$$v^2 = 0 + (2 \times 9.81 \times 1)$$

$$v^2 = 19.62$$

$$v = 4.429\text{ms}^{-1}$$

During the impact at maximum depression final velocity will be zero:

$$v^2 = u^2 + 2as$$

$$0 = 19.62 + (2 \times -50)s$$

$$s = 0.0196\text{m}$$

Depending on the properties of the foam, it will be capable of compressing up to 75% of its original thickness (Kuncir, Wirta and Golbranson, 1990). Therefore for this theoretical model the initial foam thickness would be required to be 26.7mm thick.

If we now consider the foam to also include damping properties, then if the foam were critically damped, then the maximum deceleration occurs at time zero due to the displacement response of critically damped materials (Figure 5.7).

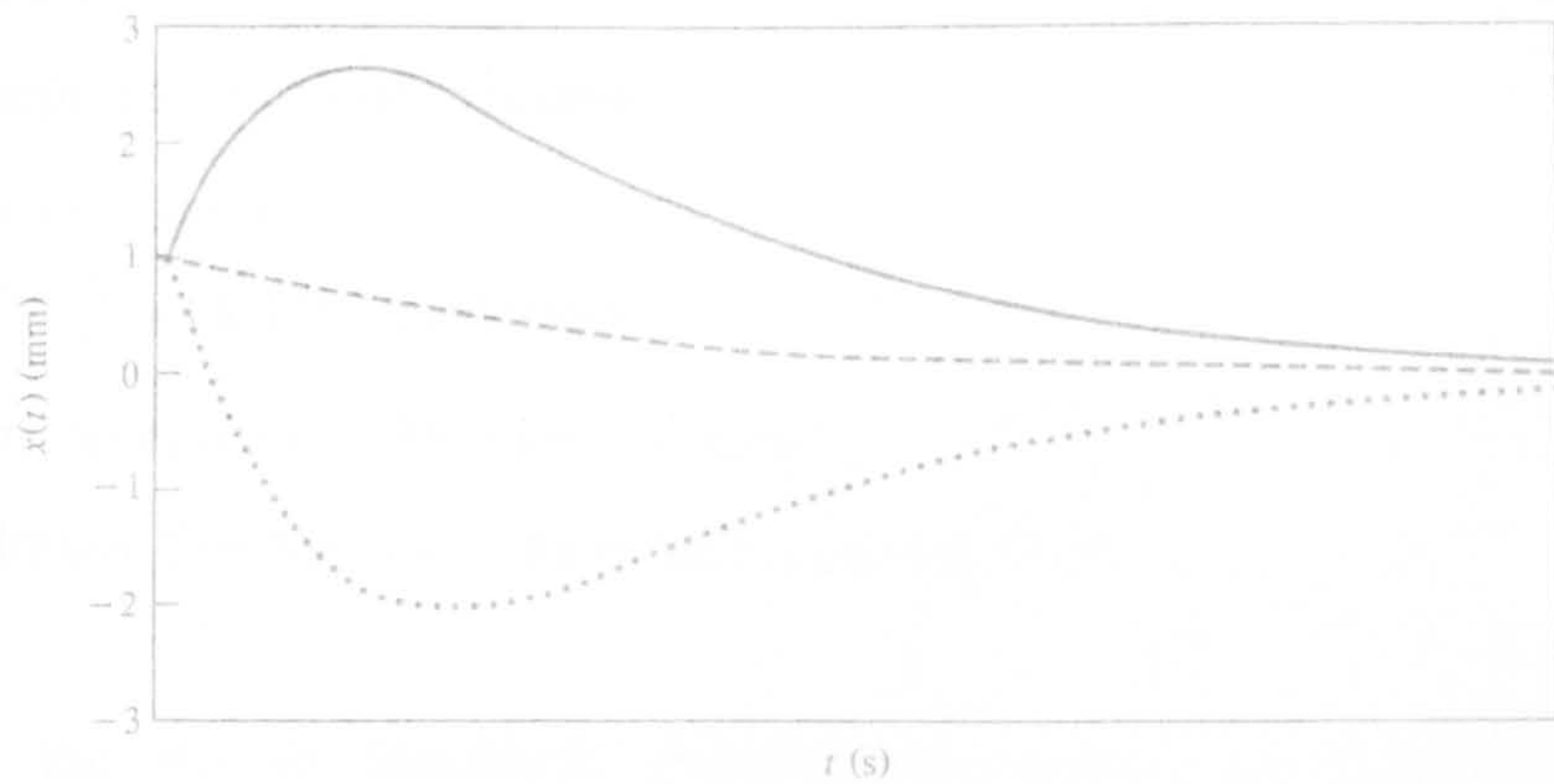


Figure 5-7: Critical damped response (adapted from Graham Kelly, 1993).

For a critically damped response, the displacement function with respect to time can be used to establish the maximum depression of the foam.

Firstly the spring and damping characteristics need to be calculated:

At $t = 0$ $\ddot{x} = 50g$, $x_0 = 0$ and $\dot{x} = 4.429 \text{ m/s}$, for an 8kg mass being dropped from one metre. As the force due to acceleration $F = ma$, and spring force $F_s = kx + c\dot{x}$, then if the deceleration is due to the material properties: $kx + c\dot{x} = ma$

Substituting in the known values above:

$$k(0) + c(4.429) = 8 \times 50 \times 9.81$$

$$\therefore c = 885.9 \text{ N/ms}$$

For critically damped systems $c^2 - 4mk = 0$

$$\therefore c^2 = 4mk, \frac{885.9^2}{4 \times 8} = k$$

$$\therefore k = 24529.9 \text{ N/m}$$

Now considering the time dependent displacement function for a critically damped response: $x(t) = e^{-\omega_n t} [x_0 + (\dot{x}_0 + \omega_n x_0)t]$ (Graham Kelly. S, 1993), at maximum depression $\dot{x} = 0 \text{ m/s}$, therefore if we differentiate the expression for displacement and put it equal to zero, the time at which maximum depression occurs can be calculated:

$$\dot{x}(t) = 0 = -\omega_n e^{-\omega_n t} [x_0 + (\dot{x}_0 + \omega_n x_0)t] + e^{-\omega_n t} [\dot{x}_0 + \omega_n x_0], \text{ rearranging for } t \text{ gives:}$$

$$t = \frac{\dot{x}_0}{(\omega_n \dot{x}_0 + \omega_n^2 x_0)}, \text{ where } \omega_n = \sqrt{k/m} \text{ for a critically damped system, } \omega_n = 55.37 \text{ rad/s.}$$

Substituting in the values for k , m , x_0 and $\dot{x} : t = 0.0181s$, and using this value of t the maximum depression can be calculated:

$$x(t) = e^{-\omega_n t} [x_0 + (\dot{x}_0 + \omega_n x_0)t]$$

$$x(t) = e^{-(55.37 \times 0.0181)} [0 + (4.429 + 0)0.01081]$$

$\therefore x$ at maximum depression = 29.5mm, if the foam is assumed to depress up to 75% of its original thickness, this foam will have had a starting thickness of 39.3mm.

Besides the British Standards requirement for maximum acceleration, the exposure of the rails must also be considered. As the linear guides have been specified as type SHS 15C, the height of the rails alone is known to be 16mm. It is therefore important that the foam used when fully depressed still covers the rails leaving no metal exposed for the gymnast to land upon. For critically damped foam this would require a starting thickness of 39.3mm, producing a thickness of 9.8mm when fully depressed ($39.26\text{mm} - 29.45\text{mm} = 9.82\text{mm}$). Comparing the thickness of the foam when fully depressed to the depth of the rails, it was calculated that a further 6.2mm of foam would still be required if the rails were not to become exposed ($16\text{mm} - 9.82\text{mm} = 6.18\text{mm}$). the required thickness of the foam was therefore calculated to be 45.4mm ($39.26\text{mm} + 6.18\text{mm} = 45.4\text{mm}$).

Experimentation

Using a British Standards specified 8kg impactor, trials were carried out on various foam samples to achieve the deceleration properties of the various materials and combinations of materials. Several foam samples were obtained from Azote Foams plc.

The best combination of the standard foams was found to be 50mm of soft VA80 (SH value 63) foam, with a further 5mm layer of 38kg/m visco-elastic foam on top. Visco-elastic materials have exceptionally high energy dissipation qualities, however as they efficiently dissipate energy, initial contact forces are high. The combination of foams used had the high energy dissipation properties of the visco-elastic foam combined with the soft compressive properties of the VA80 foam which reduce the high initial forces induced by the visco-elastic foam. The overall initial thickness of the foam was also only 10mm thicker than the theoretically predicted thickness for a critically damped material. This result may be due to the compression properties of the foams tested. For the prototype training aid 55mm of foam will be used to cover exposed sections of the equipment where possible in accordance with British Standards. The flame retardant properties of the foam have not been tested due

to lack of appropriate facilities. However Azote Foams plc. have various flame retardant grades of foam, and so if taken into production, a suitable foam would be specified.

5.6 Detailed design

In this section the conceptual idea will be developed into a complete concept and failure analysis will be performed on the complete concept to establish any weaknesses in the design.

5.6.1 Complete concept

The minimum shoulder width of the gymnasts analysed in Yeadon and Trewartha (2003) was 230mm for a gymnast of age 13 years, and gymnasts much younger than this would potentially use the training aid so consequently it was important for the training to have a narrower usable minimum width than 230mm.

It was decided that the top set of rails, providing the sideways movement was not to overhang the bottom set of rails by any amount. This was to ensure that no torque could be induced when the training aid was at the extremities of its movement. Therefore on both the right and left pair of bottom rails, the two rails must only be set as wide as the length of the top rail (Figure 5.8). This provided a constraint of the design.

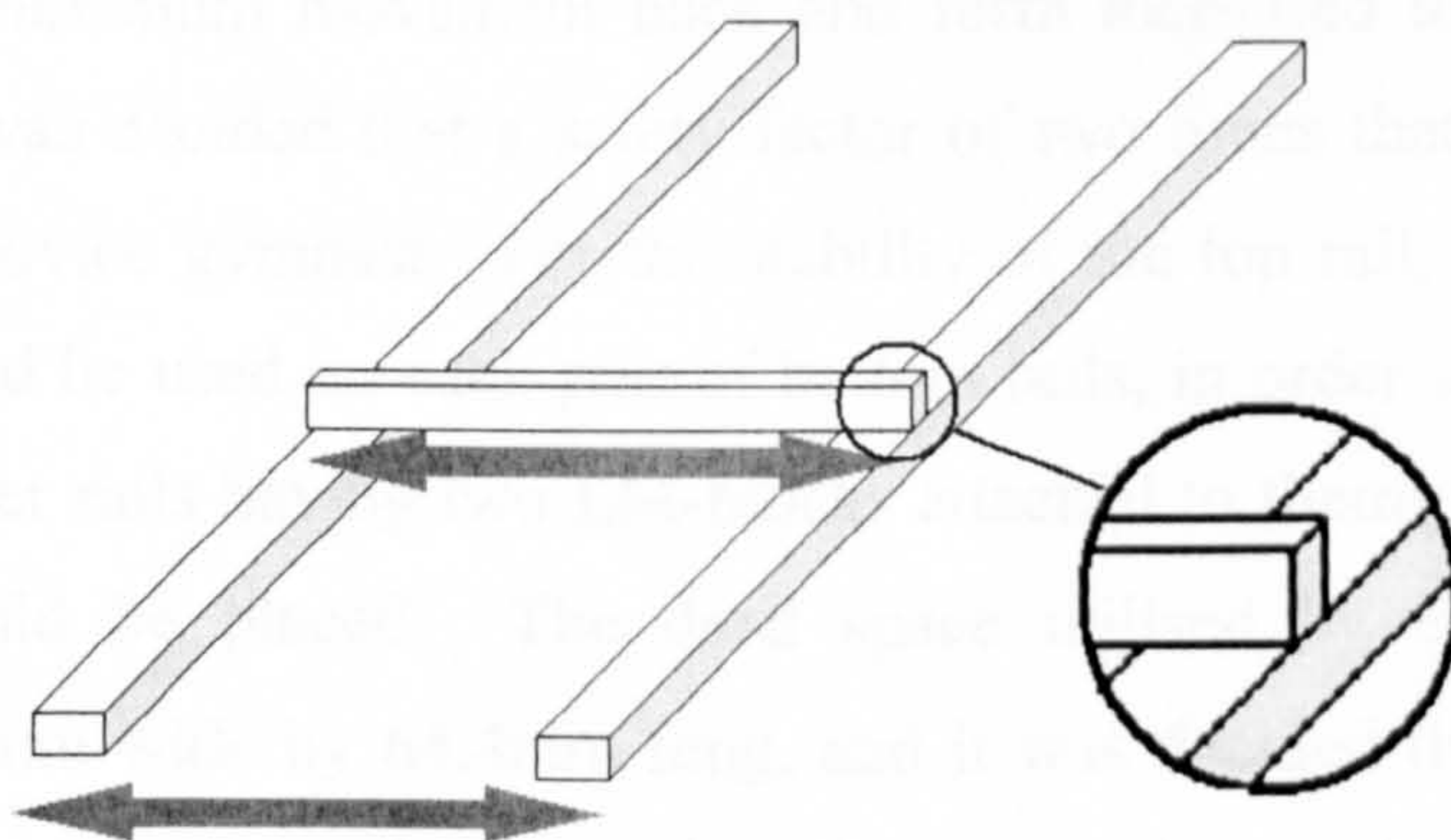


Figure 5-8: Limitation to rail layout (not to scale).

From the data collected in Chapter 4, it had been established that during the worst balanced handstand (trial 3), the average distance between the wrists was 400mm with a maximum displacement of 225mm for each wrist for a gymnast with a shoulder

width of 374mm. The largest instantaneous sideways movement measured during the trials had a range of 850mm. Using two standard rails with a length of 340mm each, would therefore ensure that there would sufficient space for the movement required.

With two standard SHS-15C 340mm rails, at a distance of 200mm from each other, taking into account the slider block overhang of 16mm and taking into account the dead space of 32.2mm used by the blocks at each end of the rails, the final usable length was calculated to be 768.6mm and similarly a minimum displacement of 217.4mm (Figure 5.9). This was considered to be suitable dimensions for a training aid for novice gymnasts, however the design dimensions would be tested practically through evaluation of the prototype training aid.

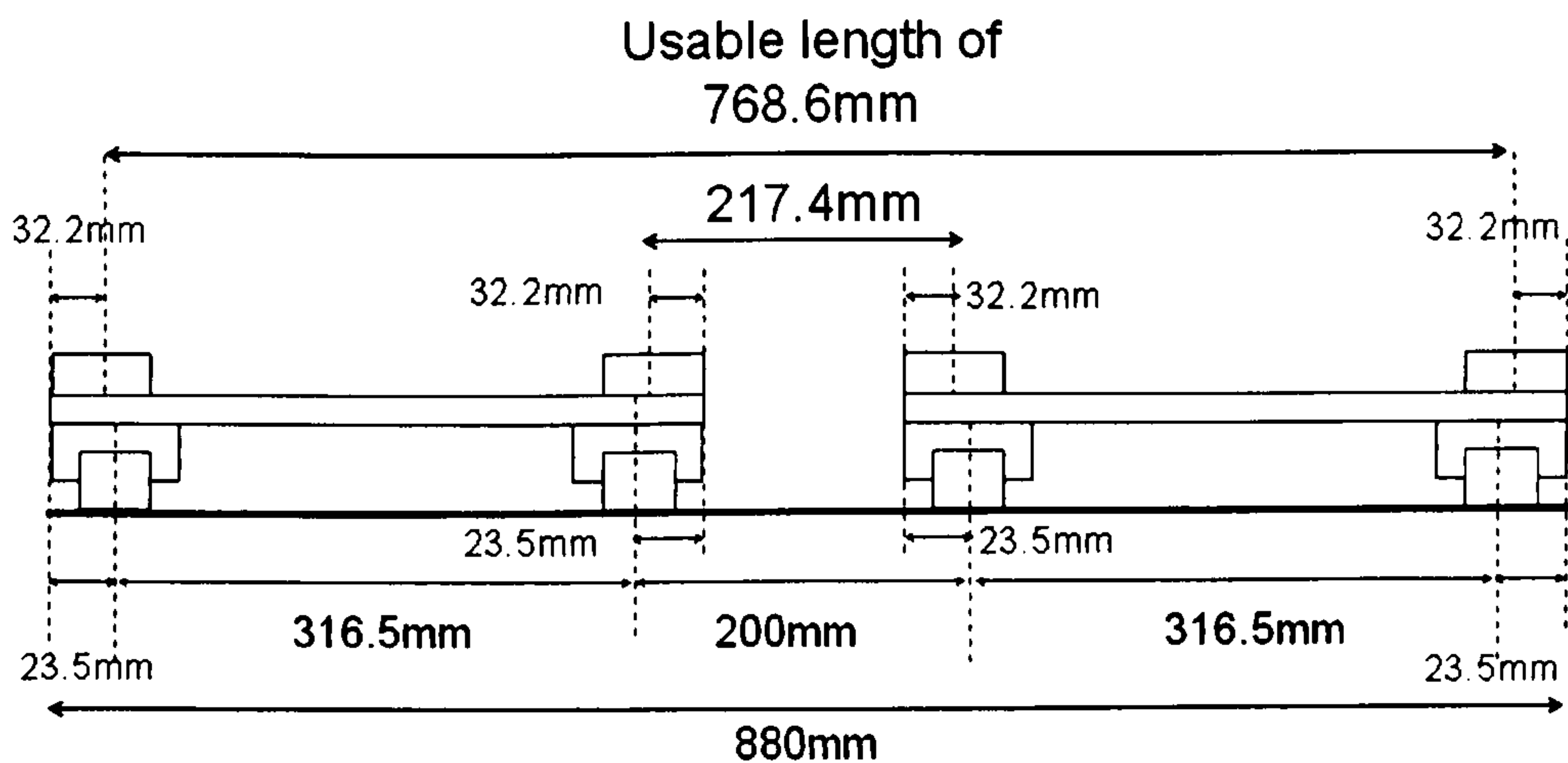


Figure 5-9: Dimensional set-up for the bottom set of linear rails (not to scale).

With the maximum movement back and forth measured to be 180mm for an elite gymnast, it was decided that a safety factor of two times that distance would be acceptable for a novice gymnast. For the stability of the top rail, it was decided that three blocks should be used on each pair of bottom rails, in order to make a triangular base (with the outer rails having two LM-blocks attached to them) upon which the top sideways rail could be placed. The dead space utilised by each LM-block had dimensions of 47mm wide by 64.4mm long, and it was decided that 50mm clearance would be sufficient to attach a 16mm wide rail between the two block. This made the dead space on the bottom rail a total of 178.8mm long (Figure 5.10), therefore using a standard rail length of 700mm left a usable length of 521.2mm which was almost three times the distance utilised during the hand balance by the elite gymnast.

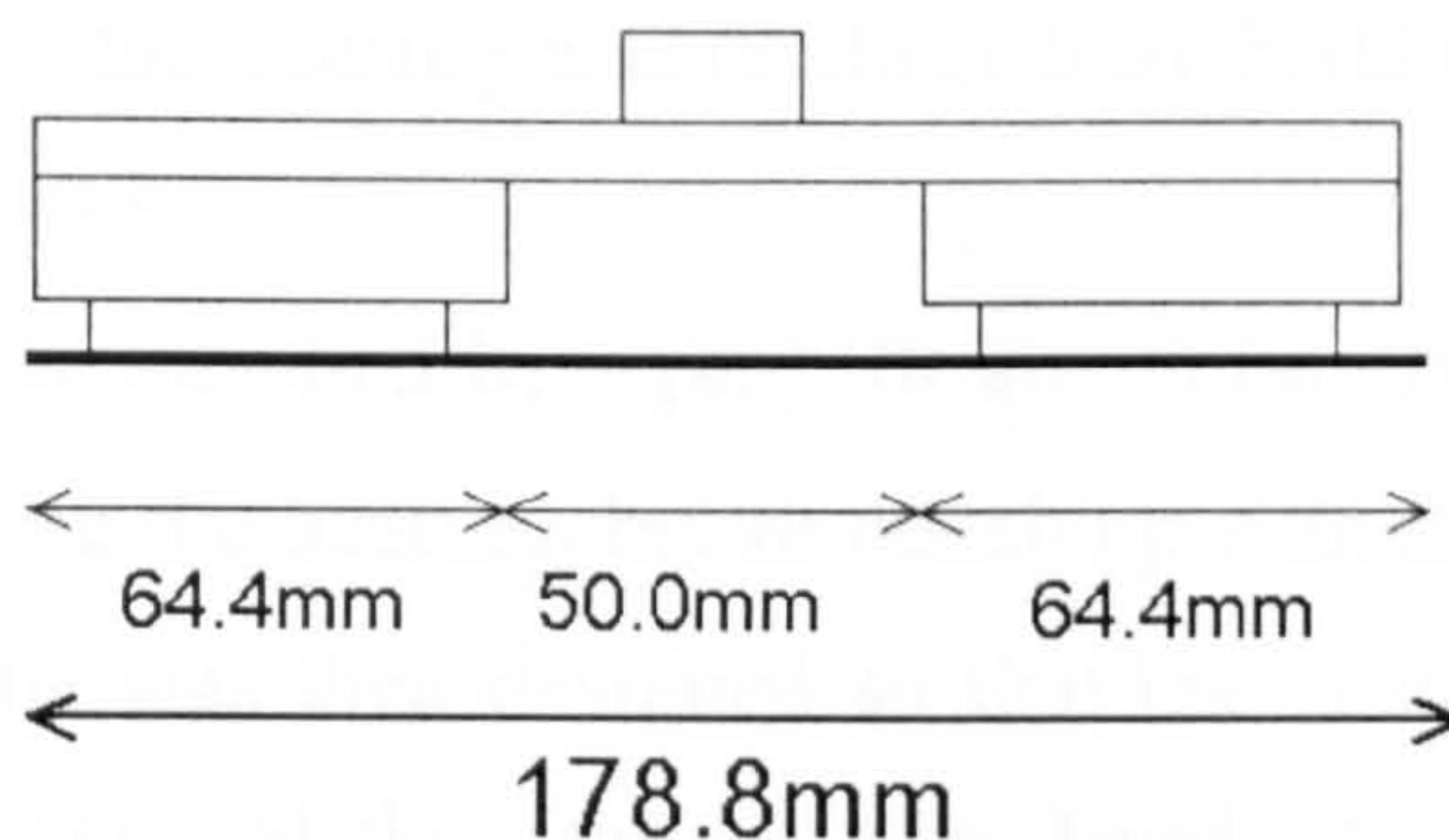


Figure 5-10: Dimensional set-up for the top set of linear rails (not to scale).

As the positioning of all of the rails had been calculated, the one remaining dimension to determine was the height constraint of the various layers of the training aid. This would be mainly determined by the component size, but also by the foam thickness requirement of the British Standards BS EN 913:1996 discussed in Section 5.5.3.

As the overall height of the SHS 15C rail and block combined is 24mm, it was decided that on top of the bottom set of blocks would be added a 33mm high plinth, with the same top surface dimensions as the blocks i.e. 64.4mm x 47mm. This was to provide enough clearance for the 55mm of foam which would be placed around the rails. A 2mm clearance gap was given between the top surface of the foam and the upper layer of the training aid to ensure the smooth fluid motion of the training aid during use (Figure 5.11).

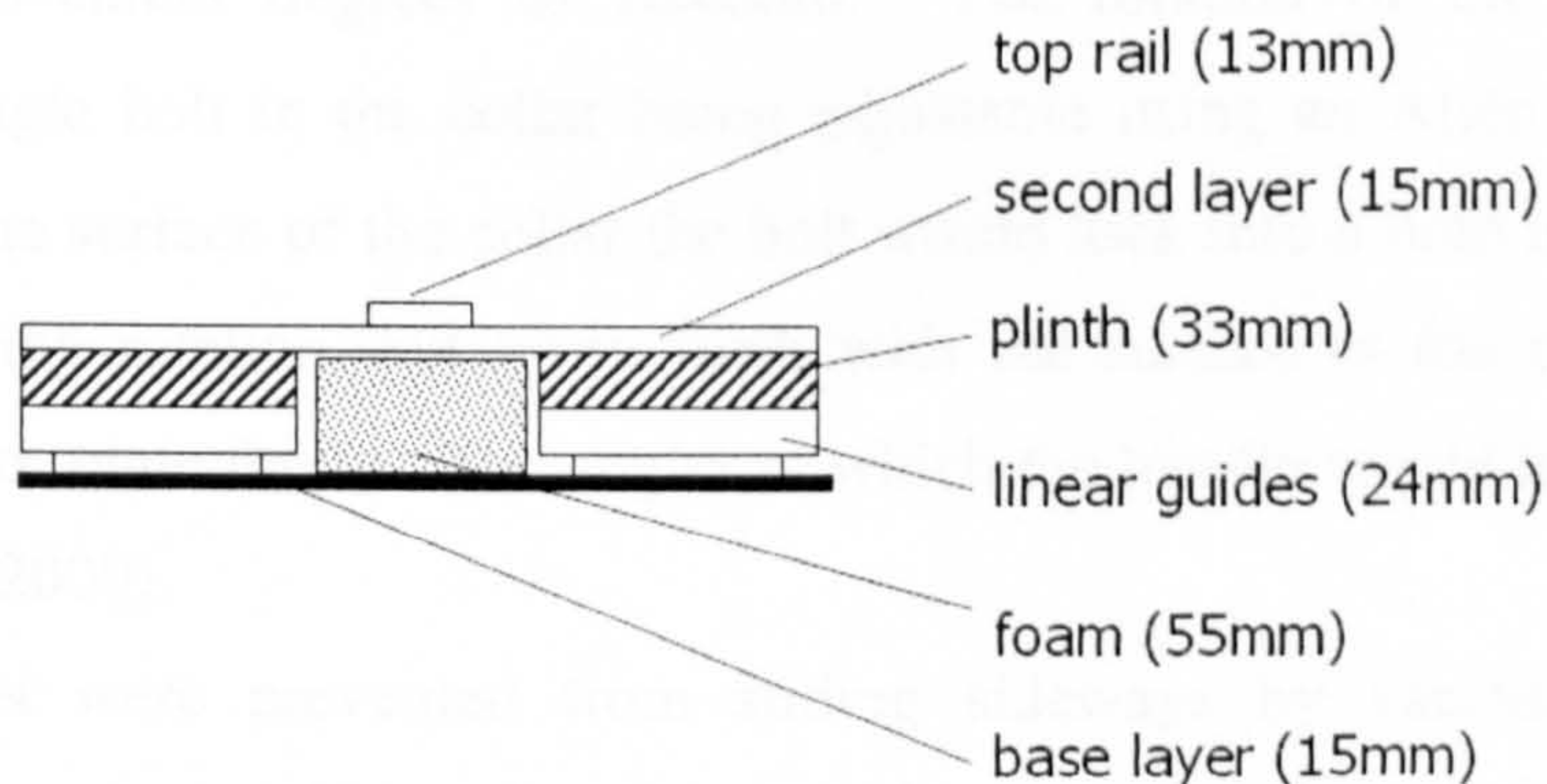


Figure 5-11: Side view of base and second layer (not to scale).

The final stage of the design was the attachment of the handle. For this a FAG angular contact ball bearings 3203-B-TVH was used. This component had a basic load static rating of 14400N and a dynamic rating of 8650N. As specified earlier the maximum loading was estimated at being only 1000N and so the bearing was suitable. As the loading was to be axial through the bearing and there was limited information

available for this application, the bearing was confirmed by FAG engineers as the most suitable bearing for the purpose.

The bearing was to be attached by a push fit aluminium collar which would be dimensioned to not only house the bearing, but to match up with the pre-tapped holes in the slider blocks. The handle was then designed so that the neck of the handle was a push fit with the inner diameter of the bearing. The handle was made from steel in order to be durable, and was profiled to have the same curvature as the rings. Sufficient clearance was given between the handle and the base of the handle to allow smooth rotation to occur (Figure 5.12).

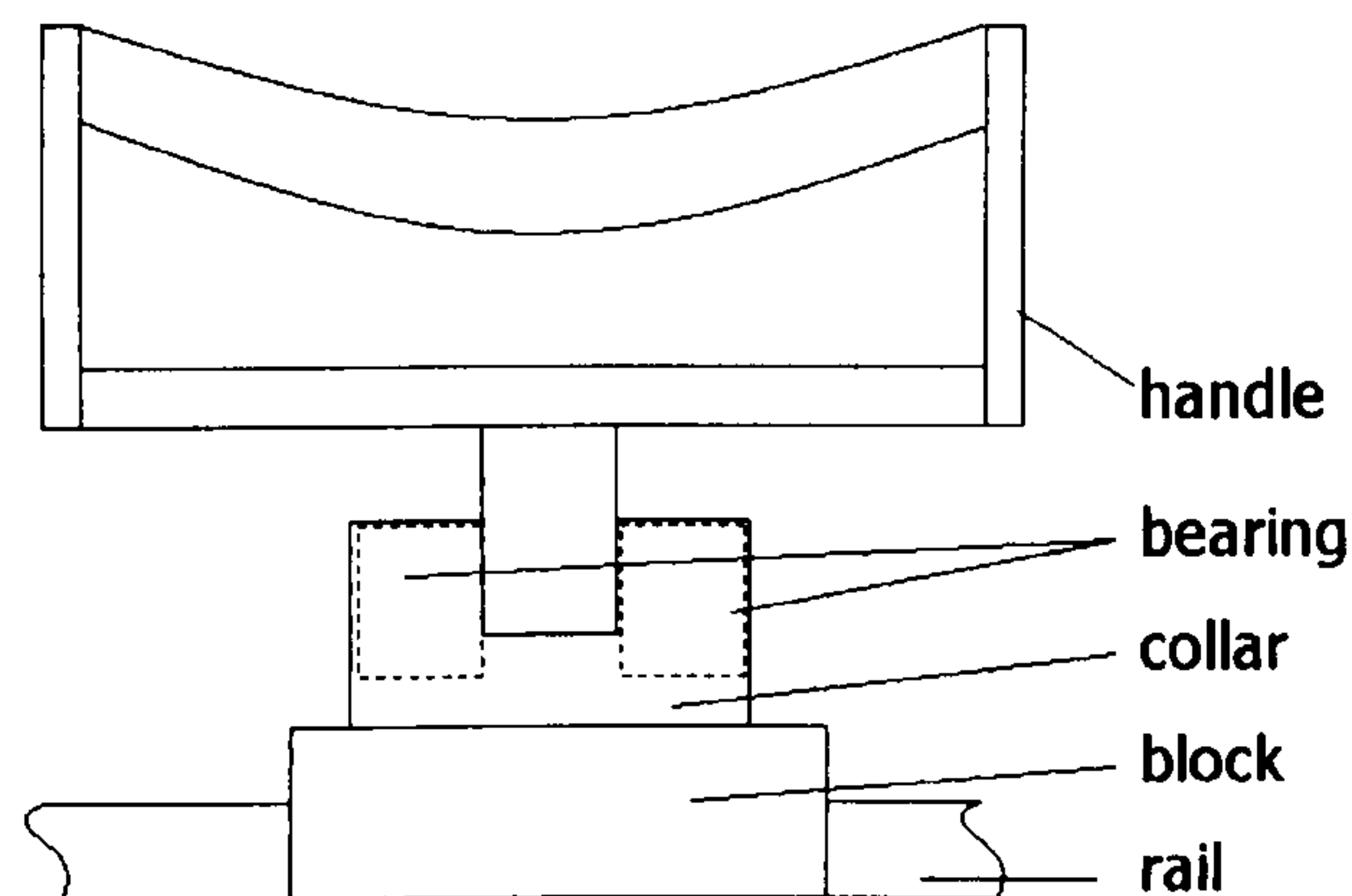


Figure 5-12: Handle assembly (not to scale).

With the training aid fully designed, the last considerations were the methods of controlling the movement degrees of freedom. The rotation of the handle was controlled by a single bolt in the collar being adjustable using an Allen key. When protruding above the surface of the collar the bolt would lock into a hole in the base of the handle preventing rotation, but when flush with the surface of the collar, would permit the handle to rotate freely. The angles at which the handle would lock were 30° and 45° (Crumley, 2000).

The handles were prevented from sliding sideways by various removable locking pins. These pins could be placed in a variety of holes, locking the top set of slider blocks into a location suitable for the individual gymnast. The final movement restriction was the synchronised forward and backward motion of the bottom set of slider blocks. This was achieved by a metal bar with two pins either side being designed to slot into four existing holes on the second layer of the training aid. Once in location the four pins prevented the right and left handles from moving back and forth separately. None of the pins or bolts were fastened tightly, and so they could be adjusted quickly and easily by hand.

5.6.2 Failure analysis

With a complete concept produced, it was necessary to perform a failure analysis of the design. This would highlight any weaknesses or flaws in the design before the full engineering drawings were produced and before a test prototype was manufactured.

Fault Trees

Fault trees are used as a method of analysis to identify which component failures might be responsible for particular system failures. Using 'AND' and 'OR' gates, system failures modes can be identified using a top-down approach to constructing a fault tree. During this approach, with the top level being system failure, and using a logical tree like construction, Wright (1998) explains that the relationships between the lower level order failures can be described, resulting in the determination of basic events which would result in the system failing.

The first failure analysis to be performed was the production of a fault tree. This was to portray the various modes in which the training aid could stop functioning. This required an analysis on a basic level of each component and how the failure of the components may prevent the training aid from functioning properly (Figure 5.13)

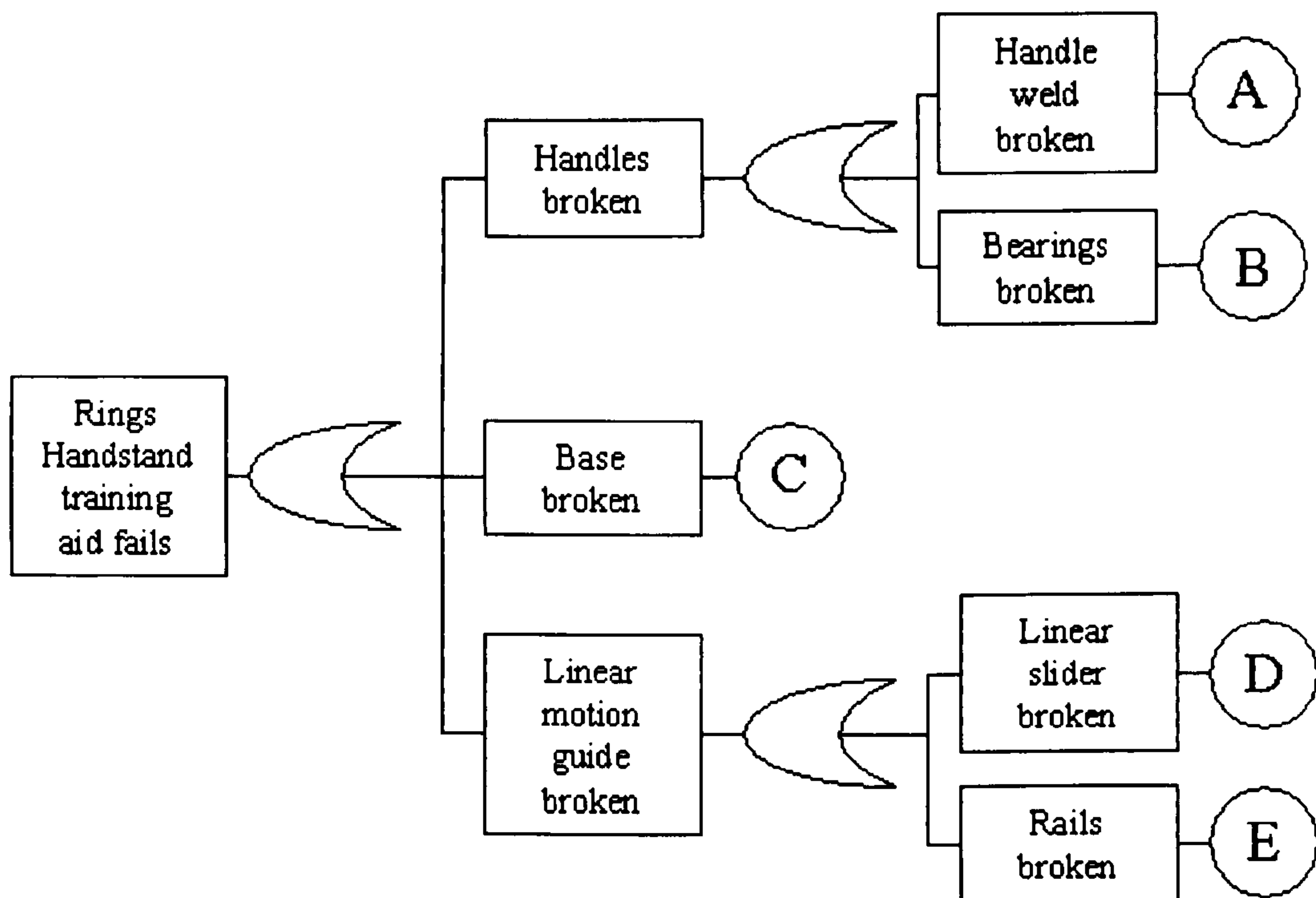


Figure 5-13: Fault tree for the rings handstand training aid.

Identifying the possible faults of the design prevents poor concepts becoming prototypes. However it is necessary to expand the fault tree so that more information can be first collected on the possible failure modes.

Failure Modes and Effects Analysis (FMEA)

With the possible system failures identified by the fault tree, an investigation to find out how such failures could occur, and what combination of component failures may give rise to them must take place. Wright (1998) explains that this information along with assigned severity ratings of component failures, the probability of such failures occurring, and a description of by what method the failure would be detected, can all be arranged within an FMEA worksheet. The worksheet can then be used to identify critical components and make recommendations for design improvements.

An (FMEA) worksheet was to be developed for the prototype rings handstand training aid (Figure 5.14). Due to the large number of safety factors involved in the design and in the component choices, the probability of all failure modes was low, although if one were to fail it would have a significant effect of the usability of the training aid. With this in mind only components with a large safety factor will be utilised in the design. For the bottom set of linear guides, two rails and three slider blocks will be used on both sides greatly reducing the applied loading calculated for standard use. Further to the failure analysis the requirements of the British Standards BS EN 913:1996 must also to be considered during the design phase if the concept is to pass the British standard tests once the prototype is built.

Item	Description and function	Failure mode	Failure effects		Detection method	Severity (1 - 5)	Probability (1 - 5)	Remarks
			Local	System				
A	Handle: Gymnast holds during balance	Fracture or deform	Gymnast can not hold handle	Training aid rendered useless	Observation only	5	1	Unlikely to occur due to over engineering
B	Handle bearings: Permits rotation of the wrist during balance	Seized	Handle will not rotate	The training aid will lose an important movement degree of freedom	Lack of rotation	4	1	Lateral rotation is the second most important mode of movement
C	Base: Upon which the aid is built	Fracture	Base will become less rigid	Training aid will lose rigidity	Observation only	5	1	Base is always flat on a solid floor
D	Linear motion slider: Provides low friction linear motion	Fracture, deformation or seize	Slider-rail mechanism will not function properly	Training aid will lose fluid motion or at worst be rendered useless	Lack of smooth motion	3 - 5	2	Design calculations performed to reduce probability, and the training aid must be kept clean and away from constant dust
E	Linear motion rails: Provide low friction linear motion	Fracture or deformation	Slider-rail mechanism will not function properly	Training aid will lose fluid motion or at worst be rendered useless	Lack of smooth motion	3 - 5	2	Design calculations performed to reduce probability, and the training aid must be kept clean and away from constant dust

Figure 5-14: FMEA work sheet for the rings handstand training aid.

5.6.3 British Standards requirements

All of the materials specified for the design should adhere to the required BS fire standards. As only wood and steel, with a layer of foam are to be used, both the wood and foam will need to be fire retardant. The frictional properties of the foam for this specific design are not relevant as the gymnast will not be in contact with the foam surface during any movement.

With regards to structural safety and integrity, the training aid must have no sharp edges or protruding parts. As the edges of the rails will be covered by foam the design conforms to this requirement. There must also be no shearing or crushing points, and no danger through unintentional dropping of the equipment. The equipment must be stable, strong, and shock absorbent, and withstand British Standards testing (BS EN 913:1996). Due to the design of the handle, there are no shearing or crushing points within the design as all gaps have been minimised to prevent these situations from occurring.

5.6.4 Final design

The final design of the rings handstand training aid was modelled in Unigraphics. All accumulative dimensions were checked, and the design prototype was produced as a three-dimensional solid model (Figure 5.15) to enable a visual check of all design details.

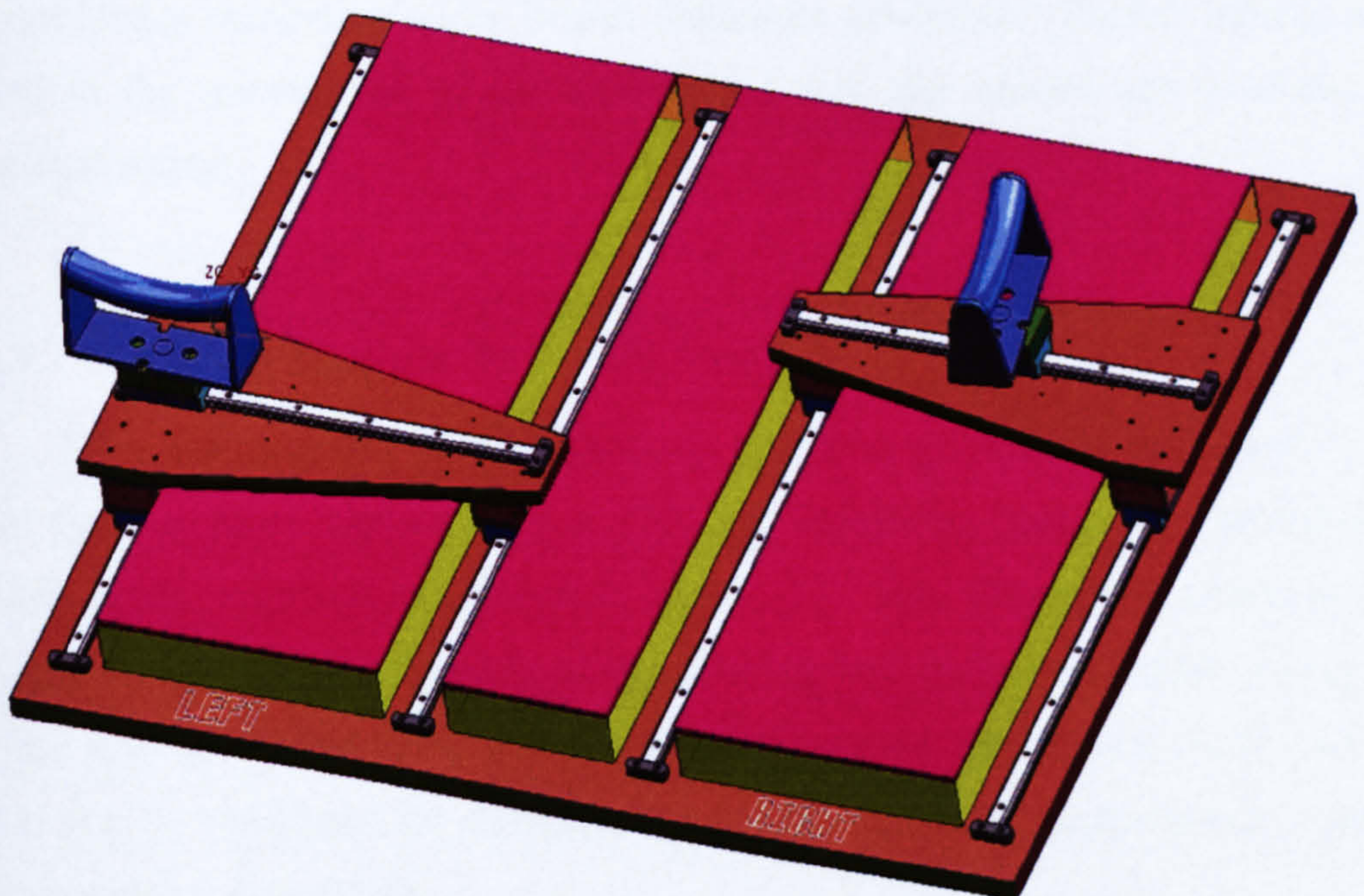


Figure 5-15: Final design concept

5.7 Chapter summary

This gymnastics training aid has been carefully designed to train gymnasts to maintain a hand balance on the rings. It has been designed to fulfil all established customer requirements and to pass the required British Standards. The design concept has been proved through the theoretical analysis of the control involved in maintaining balance during a handstand on the rings, and through the comparison of the rings technique with the technique theoretically used on the training aid.

Fault and failure analyses have been performed, and all reasonable safety aspects have been considered. It was decided that the design was suitable for prototype manufacture. Once built the prototype will be physically tested in accordance with British Standards, and to confirm the results of the FMEA analysis. No person shall be permitted to use the training aid until it has been deemed safe to do so. The training aid has been designed from data collected on an elite senior male gymnast, and once deemed safe will be tested by different a elite senior male gymnast to prove the design concept. Data and feedback shall be collected from both the participant and his coaches, and this will be detailed and discussed in the following chapter.

6

Handstand Training Aid Analysis

6.1 Introduction

The initial analysis involved a comparison of the handstand on the floor and the handstand on the rings. This was to enable an assessment of the handstand training aids to see which handstand type they best resembled. Movement data, muscle EMG data and force data were all collected for the purpose of this comparison.

The second part of the data collection was to analyse not only the designed training aid but also three other existing training aids which are already available for purchase. The training aids were all compared to the handstand on the floor and on the rings, and also to each other.

6.2 Safety testing

It was imperative to assess the safety of the training aid before any gymnasts were permitted to use it. The main safety testing carried out comprised tests outlined for gymnastics equipment under British Standards guidelines. Further testing, more related to the specific use of the training aid was also carried out to ensure the gymnasts' safety.

6.2.1 British Standards safety testing

From the reviewed British Standards related to gymnastics equipment, it was found that the most appropriate was "BS EN 913:1996; Gymnastics equipment – General safety requirements and test methods". This Standard required several different assessments to be made of the training aid, including impact testing and stability testing. It was imperative that this training aid should pass these tests if it was to ever be considered for manufacture. The first stage of the assessment required an observational assessment.

Surface finish

As the product is made from wood, and metal rails, it was decided that the entire training aid should be covered in a dense foam to prevent injury. Any remaining edges or corners were rounded off to make them safe during use.

Gaps and shearing/crushing points

Although there were several rails and bearings involved in the design of the product there was no danger of entrapment, since all of the components were either concealed or made from mechanisms with exceptionally tight fits.

Unintentional dropping

Unintentional dropping was not considered to be a problem as no transport system is to be used to move the training aid as it has a mass of only 19.2kg in total. Due to its size however, it will need two people to move it.

Strength and stability

In accordance with BS EN 913, Annex B, a load of 1120N was applied statically to the training aid for the duration of 1 minute (+0.1s). After 30 minutes (+30s), any deformation of the training aid was measured. The load was calculated using the equation given in Annex B of the standard: $F_b = m_b \cdot a \cdot C_d \cdot S + F_s + L_v$, detailed in Chapter 3. No deformation tipping or sliding was observed at any time during the test.

Adjustment devices:

Adjustments needed to be made with an Allen key, to remove and reposition screws. Therefore no accidental changes to the training aid could occur during use.

Shock absorption of top padding

The training aid was tested in accordance with Annex C of EN 913: 1996. In accordance with the standard, an 8kg metal indenter, with a diameter of 78mm and a bottom radius of curvature of 500mm was dropped from a height of 1 metre above the highest point of the training aid. The indenter had an accelerometer rigidly mounted on the top and was dropped onto the top padded area of the training aid. The test was carried out five times at the same location, at intervals of 2 minutes. The deceleration was measured to be 472.5m/s^2 (2.d.p) (48.16g).

Conclusion

The training aid has been tested using the required assessments outlined within the British Standard EN 913:1996, and has met all of the required standards. It will however be necessary if the product goes into manufacture, for the relevant company to have the training aid fully assessed at a British Standards test centre.

6.2.2 Further safety testing

As the British Standard mainly tested the stability and strength of the training aid, it was decided that further assessments to test the training aid in a more gymnastics specific manner would be performed.

Whilst in a safety harness around the waist supported by a qualified gymnastics coach, and with safety matting either side of the training aid, an elite senior gymnast, gymnast E, with a body mass of 60kg, performed some simple safety trials. Firstly the gymnast pushed the handles with maximum strength into the end stoppers at the ends of the rails. This was to ensure that during an excessive movement, the handles could not leave the rails.

Secondly, the gymnast whilst knelt behind the training aid, and holding the handles, and applying a substantial force, performed actions similar to those used when controlling a handstand on the rings. No complications were observed. The final safety test was for the gymnast, supported in the waist harness, to stand on the handles, and to move the handles under body weight by pushing the feet in different directions. Although significant movement of the gymnast took place, and the gymnast had to fight to maintain balance, there were no components of the training aid which caused concern for the safety of the gymnast.

6.2.3 Risk assessment

To ensure minimal risk of any gymnast receiving an injury whilst performing on the training aid, it was necessary that a full risk assessment was performed.

Risk

To fully calculate the desired performance from a technological system there are factors that can be assigned when evaluating the consequences of failure to achieve. Wright (1998), considers risk to have an overall factor (R) that incorporates

R_d , the technical difficulty risk factor, and R_c , the consequence of failure risk factor, can be obtained from: $R = R_d \times R_c$. The overall risk factor (R) will range from 1 (low technical difficulty with no consequences) to 25 (high degree of technical difficulty with no backup and severe consequences), and the value or risk that a project will receive can be used to influence design considerations so as to reduce the risk factor as far as possible before manufacture.

Firstly, the risk of the project failing to meet the requirements of the product design specification was calculated (Table 6.1):

Table 6-1: Risk of technology failure – From Wright (1998)

Technology difficulty	Risk factor (R_d)
We are using existing technology with which we have personal experience, in an application identical to the one proposed.	1
We are using existing technology with which: (1) We do not have personal experience, or (2) In an application different to the one proposed.	2
We are making a new development with which we have personal experience in an application close to the one proposed.	3
We are making a new technology with which we have no personal experience or in an application different to the one proposed.	4
We are developing new technology in an area where we have little or no previous experience.	5

The risk of this project was high as no training aid had ever been developed in this manner, and the components used were not standard to the manufacture of gymnastics equipment. The value of R_d was therefore 5. Next to be assessed was the probability of the design failing (Table 6.2).

Table 6-2: Risk of design failure – Adaptation of Wright (1998)

Probability of design failure	Risk factor (R_f)
Will not occur during predictable life time of the design, regardless of any foreseen abuse of lack or maintenance. The design team have experience of the reliability of this component,	1

all aspects of the design are under the control of the design team.	
The design team are familiar with the application of the design in a similar situation and are confident that there is a low chance of failure irrespective of any foreseen abuse of lack or maintenance. All aspects of the design are under the control of the design team.	2
The design team are unfamiliar with the reliability of the design with regards to failure modes. However a third party supplier or corroborated information from elsewhere suggests the reliability is acceptable.	3
Uncorroborated evidence suggests the design will provide acceptable reliability in regards to failure modes being considered.	4
There are doubts about the reliability of this design in regard to the failure modes being considered.	5

As the main constituent components of the training aid were sourced from a well known linear bearing company (THK) and experts from the company were consulted during the design of the training aid, the risk of the design failing was medium, giving the R_f value of 3.

If the technological difficulty was then multiplied with the risk of the training aid mechanically failing, the overall project risk was calculated to be: $R_i = R_d \times R_f = 5 \times 3 = 15$. The consequence of the failure of the training aid to the safety of the gymnast was now considered (Table 6.3):

Table 6-3: Consequence of failure to the gymnast – Adaptation of Wright (1998)

Consequence of failure to gymnast	Risk factor (R_c)
It the technology fails to provide the required performance then: (1) There will be no improvement in the gymnasts ability, or (2) Existing methods will continue to be used.	1
Failure of the technology will mean that the handstand on the rings may be learnt with the wrong technique.	2
If the technology fails there is possible risk of: (1) Slight injury, or (2) Increased anxiety for the gymnast.	3

If technology fails there is possible risk of significant injury.	4
If the technology fails there is certainty of significant injury.	5

The risk of the equipment failure with regards to the safety of the gymnast was considered to have a value of 4. This was because even if the equipment fell apart during use, the gymnast would still only be a maximum of 200mm above floor level, and even in handstand, this would not be a dangerous distance to fall. If the risk to the gymnast was now calculated: $R_2 = R_f \times R_c = 3 \times 4 = 12$. This risk would be reduced by significant safety and failure testing taking place before any gymnasts were permitted to use the training aid. This would therefore then reduce the risk factor R_f to 2, and hence the new risk would therefore be: $R_2 = R_f \times R_c = 2 \times 4 = 8$. The majority of this safety testing had already been carried out and detailed in Sections 6.2.2.

Considering also how the influence of poor technique performed by the gymnast whilst using the training aid could affect the gymnast's overall safety, it became obvious that as mechanically safe as the training aid structurally was, if the gymnast was incapable of holding a solid handstand, or was not well enough conditioned, then there was still a risk of injury (Table 6.4):

Table 6-4: Consequence of poor technique used by the gymnast – Adaptation of Wright (1998)

Consequence of poor technique used by the gymnast	Risk factor(R_t)
<p>It the technique is weak:</p> <p>(1) The gymnast produces a lot of movement at the hip, inducing a lot of wobble into the balance, or</p> <p>(2) The gymnast does not manage to sustain balance, and comes down from handstand.</p>	1
The gymnast performs an average quality balance, and the hands move back and forth hitting the end stoppers at the end of the rails but maintain a handstand, or dismounts safely.	2
The gymnast performs an average quality balance, but the hands move back and forth hitting the end stoppers at the end of the rails and the gymnast falls from handstand in an uncontrolled manner.	3
The gymnast loses control of the balance, and collapses on to his head on top of the foam padded training aid.	4
The gymnast loses all control of the balance, and falls from	5

handstand falling on his back or head onto the handles of the training aid.	
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Due to this risk factor R_t being as high as possible, a value of 5 was awarded for this category of risk. It was therefore decided that to prevent injury when using the training aid, no gymnast should be allowed to use the training aid unless trained through the developed training procedure.

Recommended Programme For Use

1. The gymnast must be capable of holding a good static handstand on the floor.
2. The gymnast should then perform conditioning exercises from either a kneeling position or in front support, whilst holding the handles. These exercises should incorporate both lateral and longitudinal movements long the training aid to strengthen shoulders and body tension.
3. Once considered conditioned enough by the coach, the gymnast may perform supported performances on the easiest setting of the training aid. The training aid should be used with safety matting at the front and back of the training aid.
4. Once capable the gymnast may then perform handstand on the easiest setting of training aid alone.
5. The gymnast may then progress through the different levels of the training aid from level one to four, each time being supported until deemed safe to perform alone. Safety matting should always be used.

6.3 Data collection

The data collection took place in the Biomechanics Research Laboratory at Loughborough University on full length rings. It was not necessary for the cables to be attached to the rings frame, as it was found that they had no effect (Chapter 4) on the strain data collected. For ease of data collection, the procedure therefore took place in the research laboratory above the force plate.

Participant permission was obtained before any data was taken. A new gymnast, participated in this study. Gymnast R was a 28 year old Swiss National level gymnast, who had over 15 years experience with performing the handstand on the rings. The use of a different gymnast for the study was to ensure that the training

aid designed using data obtained in Chapter 4 from gymnast S was suitable for other gymnasts.

Obtaining data from another gymnast would also ensure that any conclusions made on the technique or control of a handstand on the rings were not only valid for gymnast S. Further elite male gymnasts will perform handstands on the training aid, in order to obtain feedback from multiple subjects.

6.3.1 Experimental set up

The equipment used for the data collection was very similar to that used in the data collection detailed in Chapter 4. Data was obtained using the Vicon motion analysis system, muscle EMG data, and strain and force data were collected. The strain data were only collected for trials performed on the rings; all other handstands took place at floor level, and so were performed on the relevant surface on top of the force plate.

Vicon

As for the data collection detailed in Chapter 4, the motion analysis system consisted of a Vicon 624 Motion Capture Data-station, eight 1280 by 1024 pixel MOS infrared M2 cameras with an aspect ratio of 5:4, all of which were short range, 17-35mm zoom lenses cameras, and three 3-port 1.3 million pixel M2 camera interface units connect the cameras to the data-station, and a host workstation. As cameras could be positioned close to the collection volume in the laboratory, it was only necessary to use eight cameras in order to obtain accurate results (Figure 6.1).

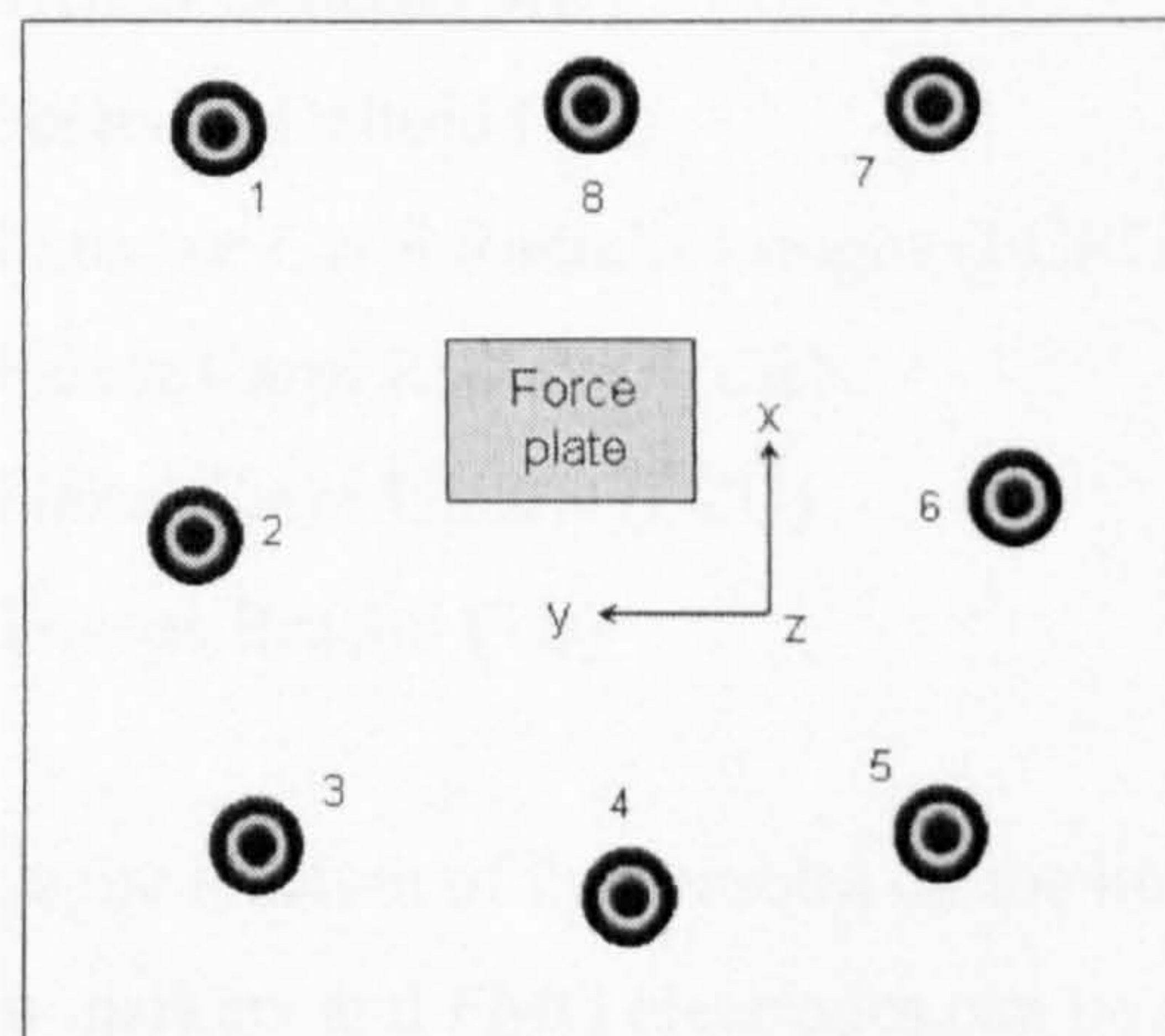


Figure 6-1: Positions of Vicon cameras around the research laboratory.

Once positioned, and with the system set up to collect data at 100Hz, static and dynamic calibrations were then performed. After each calibration, the information was reconstructed, and the results of the calibration observed. Cameras were finely adjusted, and positions altered until the mean residuals, residual range and static reproducibility were optimised.

Three calibrations were performed, and the best was saved and used for the data collection, with a mean residual of 0.969mm, a residual range of 0.357mm (1.164 - 0.807) and a static reproducibility of 0.354 %.

The same marker set as was used for the data collection in Chapter 4 was used for this data collection. As all of the training aids were close to floor level, and the rings were attached so that with the 3m cable, they were also suspended just above the force plate, it was not necessary to alter the Vicon cameras in any way once the data collection procedure had started.

EMG

Again the Bio-Vision EMG system was used, alongside the control box and mini PC to collect the muscle activation data as is detailed in Chapter 4. Ten different muscles were to be monitored, and the electrodes were positioned onto the gymnast R as follows:

- K1 - Trigger, attached to the square wave receiver
- K2 - Rectus Femoris (RF)
- K3 - Gluteus Maximus (GM)
- K4 - Rectus Abdominus (RA)
- K5 - Anterior Deltoid (AD)
- K6 - Medial Deltoid (MD)
- K7 - Posterior Deltoid (PD)
- K8 - Extensor Carpi Radialis Longus (ECRL)
- K9 - Flexor Carpi Radialis (FCR)
- K10- Flexor Carpi Ulnaris (FCU)
- K11- Triceps Brachii (TB)

Figure 6.2 details the location of the muscles on the human body. The positioning of the Vicon markers and EMG electrodes can be seen in Figure 6.3 below.

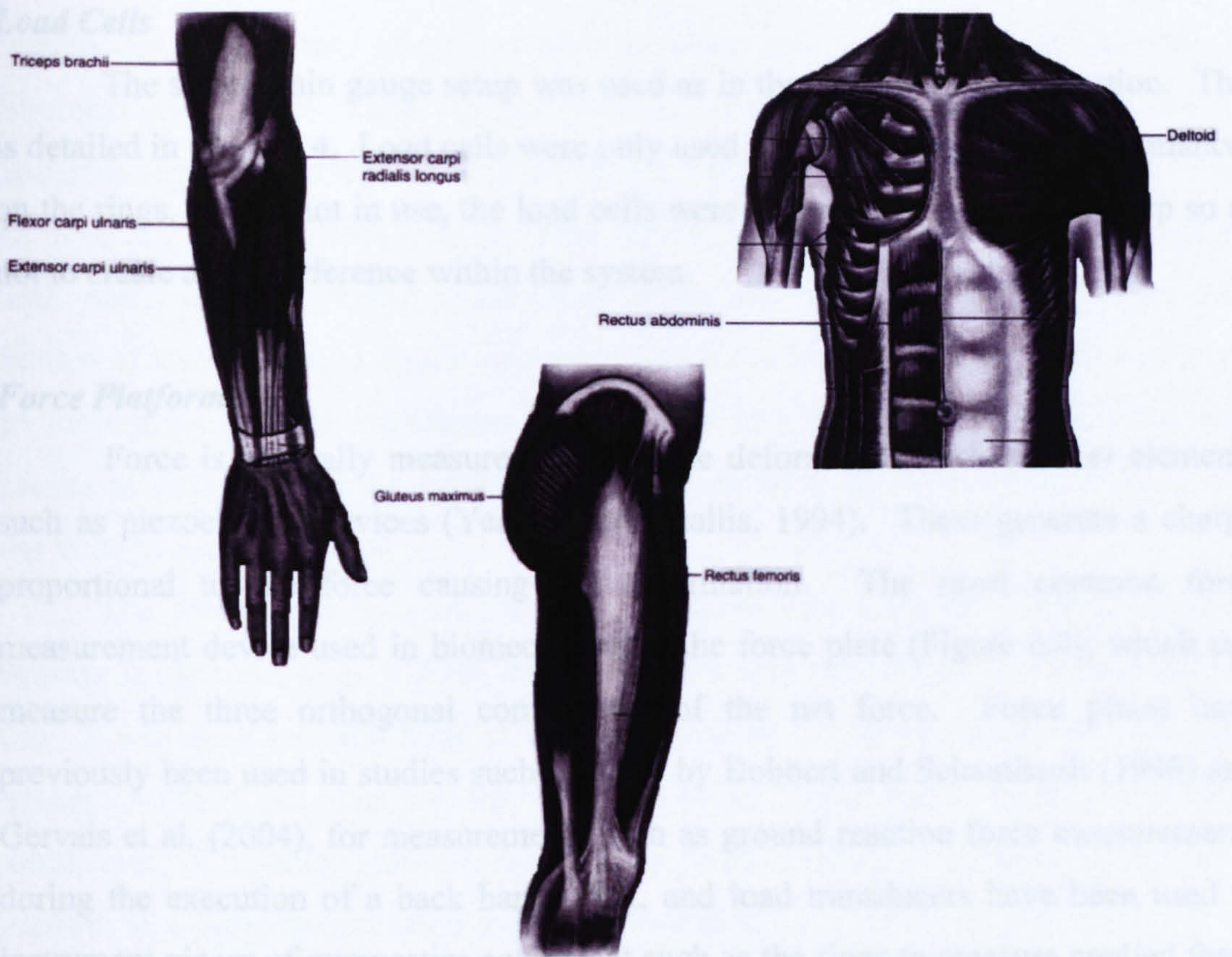


Figure 6-2: Location of muscles on the human body (adapted from Shier et al., 2004).



Figure 6-3: Gymnast R with EMG electrodes and Vicon markers.

Load Cells

The same strain gauge setup was used as in the previous data collection. This is detailed in Chapter 4. Load cells were only used to obtain data during performances on the rings. When not in use, the load cells were disconnected from the set up so as not to create any interference within the system.

Force Platform

Force is generally measured through the deformation of transducer elements such as piezoelectric devices (Yeadon and Challis, 1994). These generate a charge proportional to the force causing the deformation. The most common force measurement device used in biomechanics is the force plate (Figure 6.4), which can measure the three orthogonal components of the net force. Force plates have previously been used in studies such as those by Bobbert and Schamhardt (1990) and Gervais et al. (2004), for measurements such as ground reaction force measurements during the execution of a back handspring, and load transducers have been used to instrument pieces of gymnastics equipment such as the rings to measure applied force while being used as in the study by Brewing et al. (2000) on minimising the forces at the shoulders during the backward longswing on the rings.

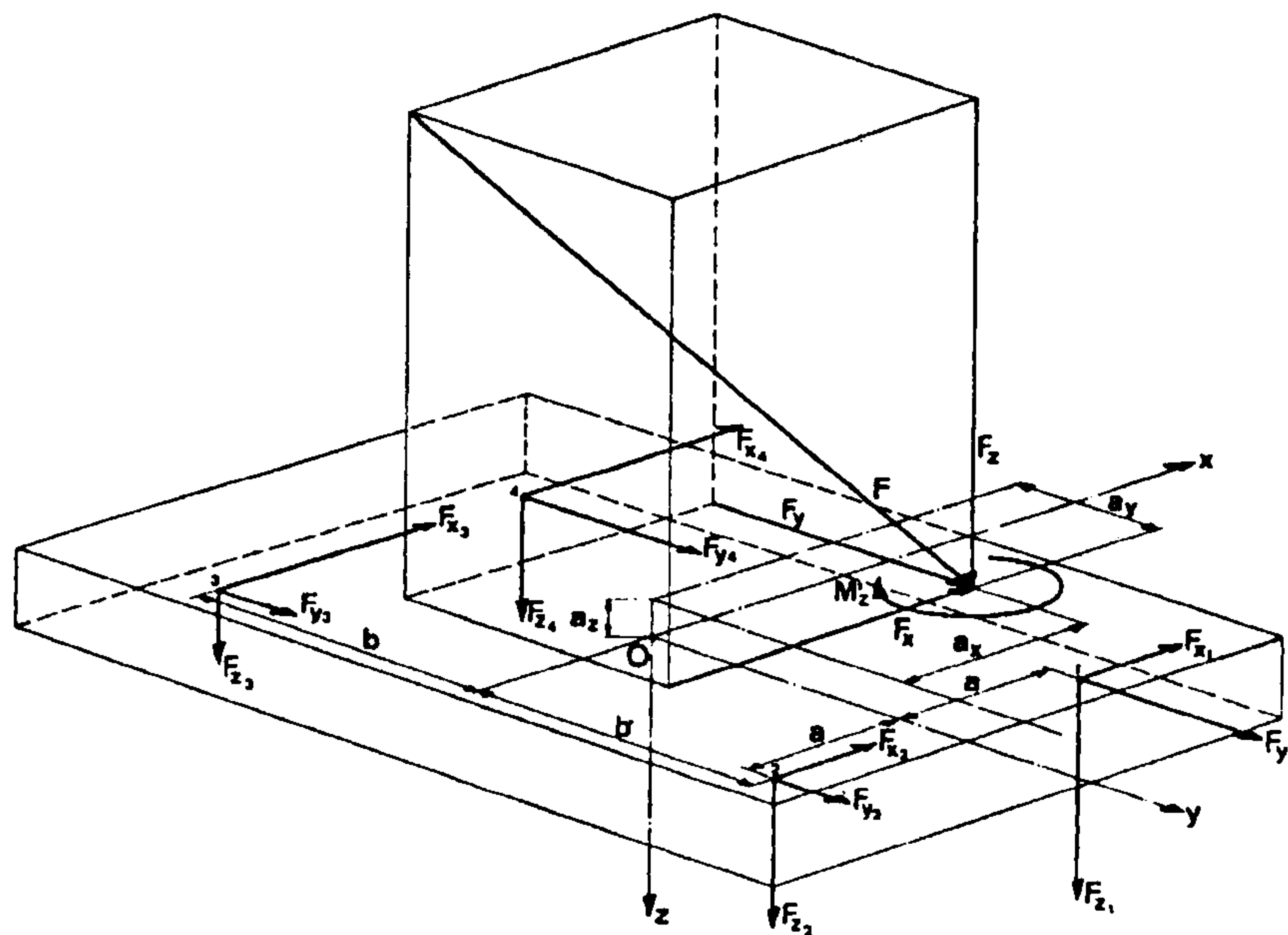


Figure 6-4:: Schematic of the Kistler force plate.

Biomechanical analyses often involve combining digitally processed analogue data with digitised image data from video. For example, performing kinetic analysis

requires the combination of ground reaction force data and kinetic data in order to determine joint forces, moments and powers. A strategy frequently employed for synchronising ground reaction force and kinetic data is to simultaneously 'mark' both the force and video records in time. This can be done with a step voltage to either an LED, which will be recorded in the image when collecting video data, or to an open channel of an analogue to digital converter which can be synchronised with data from the force plate or force transducers. O'Connor et al. (1995) explained that two such sources of data can then be synchronised by comparing the two instances when the step voltage was introduced

The force plate used in the data collection was a Kistler multi-component measuring platform, type 9281B, with a surface area of 600mm x 400mm (Figure 6.4). It was sunk into the floor of the laboratory so that it was flush with the floor surface. As the force plate was not wide enough to fit the various training aids to be tested, a rigid wooden platform was firmly fixed to the top surface of the force platform to enlarge the available contact surface area.

6.3.2 Rings and training aid data collection

Once all of the equipment was set up, had been zeroed for the correct load and had been calibrated, the data was collected. Marker coordinate data and EMG data were taken for all trials. Force data was taken for all trials on the floor, and strain data was taken for any trials on the rings.

Anthropometric Data

Anthropometric measurements of the gymnast were taken were in accordance with the model of Yeadon (1990b). Offsets from the joint centres to the corresponding marker centres were measured and recorded to enable the co-ordinate of the joint centres to be obtained from the Vicon marker displacement data. The gymnasts weighed 76.8kg with the markers and EMG equipment attached, and 75.6kg with out.

Main Data Collection Methodology

The first data taken was simply during a static trial. This was to allow comparisons between the dynamic trials and static trials to reduce any noise captured from the surrounding environment during the trials. Static trials were taken for each new piece of apparatus tested. The gymnast R was given sufficient time to rest

between repetitions and performances to ensure each skill was attempted under the same conditions.

Markers were located on each of the training aids, and on the rings cables during the data collection to enable an analysis of the actual motion of the training aids, as well as of the movement of the handstand balances. For each piece of equipment, only one trial was taken, so long as the skill was performed well.

The first skill performed was the handstand on the floor (Figure 6.5). This was performed on the wooden board attached to the force plate. The force plate was zeroed with the wooden platform attached, so that only the effective-weight of the gymnast was being measured. Secondly the gymnast performed the handstand on the rings (Figure 6.5). The load cells were zeroed for his body weight in order to obtain only changes in strain incurred through the motion of the skill.

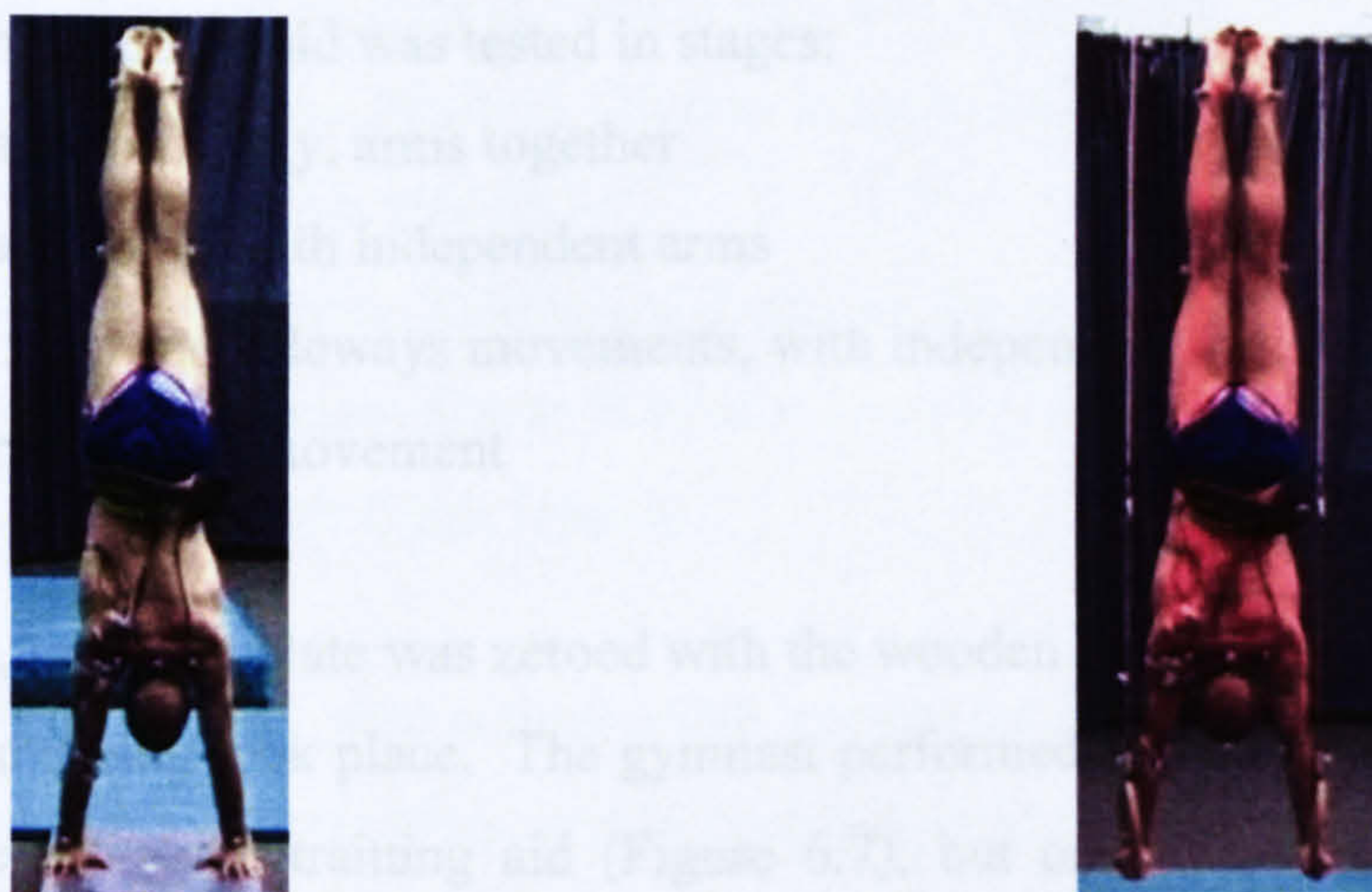


Figure 6-5: Left – Handstand on the floor; Right – Handstand on the rings.

The first training aid to be tested was the Janssen-Fritsen handstand swing. This is a lateral movement rocking device (as discussed in Chapter 3) upon which a gymnast can practice a handstand. The wooden platform was covered in gymnastics floor carpet in order to provide the same surface friction coefficient as in a gymnasium. With the wooden platform and training aid in position, the force plate was zeroed. The gymnast then performed his handstand (Figure 6.6). Following the same procedure, the handstand bowls were then tested. The bowls were two separate small hemispheres with a single wooden dowel across the diameter, on which a gymnast can practice a handstand (Figure 6.6).

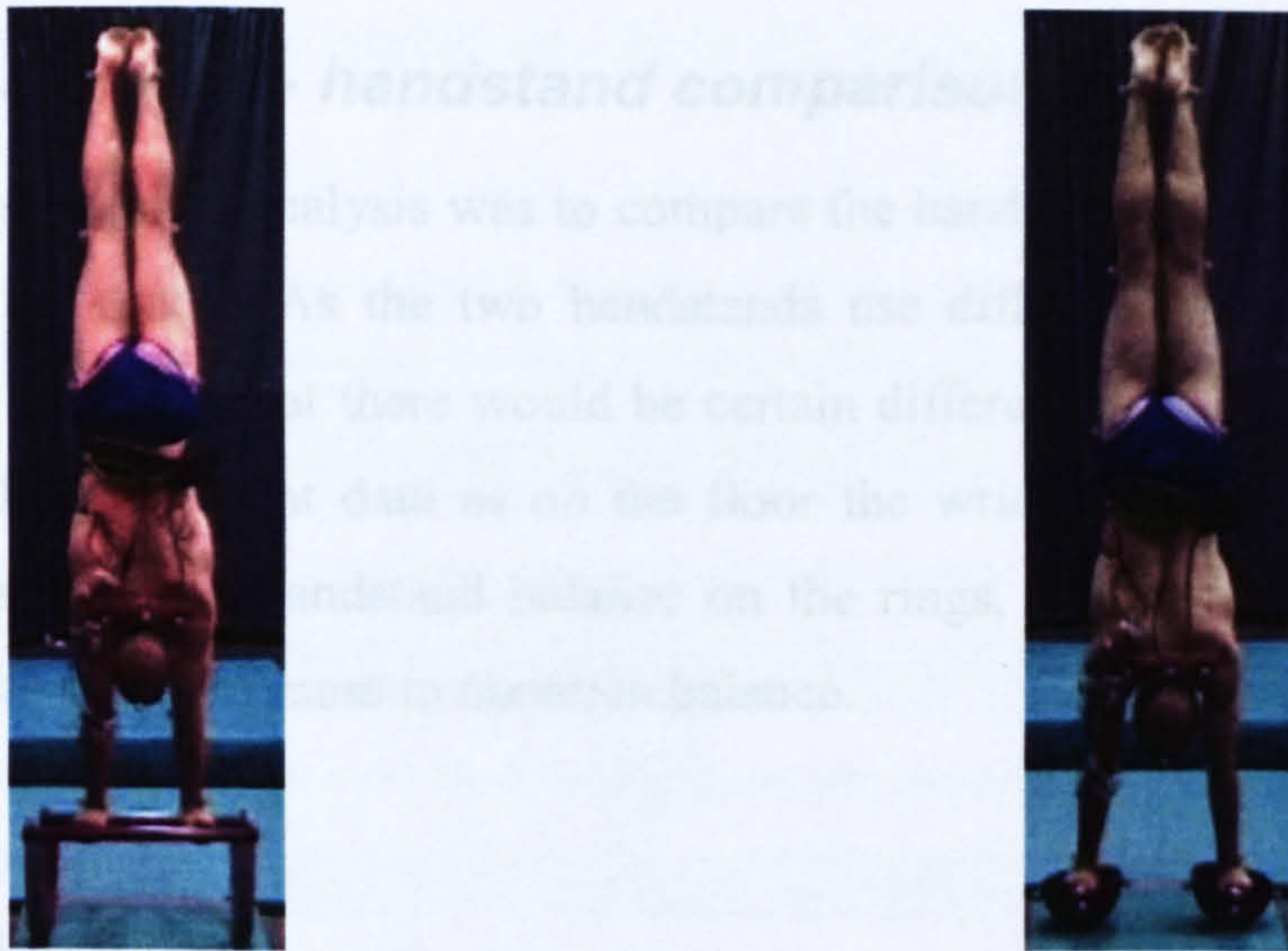


Figure 6-6: Left – Handstand on the swing; Right – Handstand on the bowls.

The final piece of equipment to be tested was the training aid designed in Chapter 5. This training aid was tested in stages:

1. Back and forth only, arms together
2. Back and forth, with independent arms
3. Back, forth and sideways movements, with independent arms
4. All directions of movement

Again, the force plate was zeroed with the wooden platform and training aid in situ before the testing took place. The gymnast performed between 2-4 trials on each setting of the prototype training aid (Figure 6.7), but only the data from the best performance (decided by an International Judge) on each setting was then used for analysis.



Figure 6-7: Handstand on the designed training aid.

6.4 Data analysis - handstand comparison

The first stage of analysis was to compare the handstand on the floor, and the handstand on the rings. As the two handstands use different methods of balance control, it was expected that there would be certain differences in the data collected, especially in the movement data as on the floor the wrist joint centres can barely move, whereas during a handstand balance on the rings, it is the wrists which are moved under the centre of mass to maintain balance.

6.4.1 Muscle data

EMG data was collected for various muscles which have considerable use during the control of a handstand (detailed in Section 6.3.1). The muscles for which the data was collected can be further divided into four categories:

1. *Body tension* - Rectus Femoris, Gluteus Maximus and Rectus Abdominus.
2. *Arms* - Triceps Brachii
3. *Shoulders* - Anterior, Medial and Posterior Deltoid
4. *Wrist* - Extensor Carpi Radialis Longus, Flexor Carpi Radialis, and Flexor Carpi Ulnaris.

Maximal isometric contractions were performed on the various muscles to enable a comparison between trials, and to enable analysis of the work carried out by particular muscles during the trial.

The initial hypothesis was that the shoulder would be used most during a rings balance and during the use of a training aid in which the action resembled that used on the rings. The wrists should be used more on the floor than anywhere else as this is the method of control when performing a handstand on the floor (Yeadon, 2003). The EMG trace for the rings should be constant as the wrist should not be moving.

6.4.2 Handstand comparison - EMG results

Figure 6.8 below contains the EMG data obtained during the maximum isometric contraction, performed by gymnast R. Figure 6.9 contains the processed EMG data of the maximal isometric contractions, and it was from these graphs that the data has been extracted. Similar graphs were also produced for all trial, and the

data has been compiled and entered into Table 6.5, Table 6.10, Figure 6.20 and Figure 6.21.

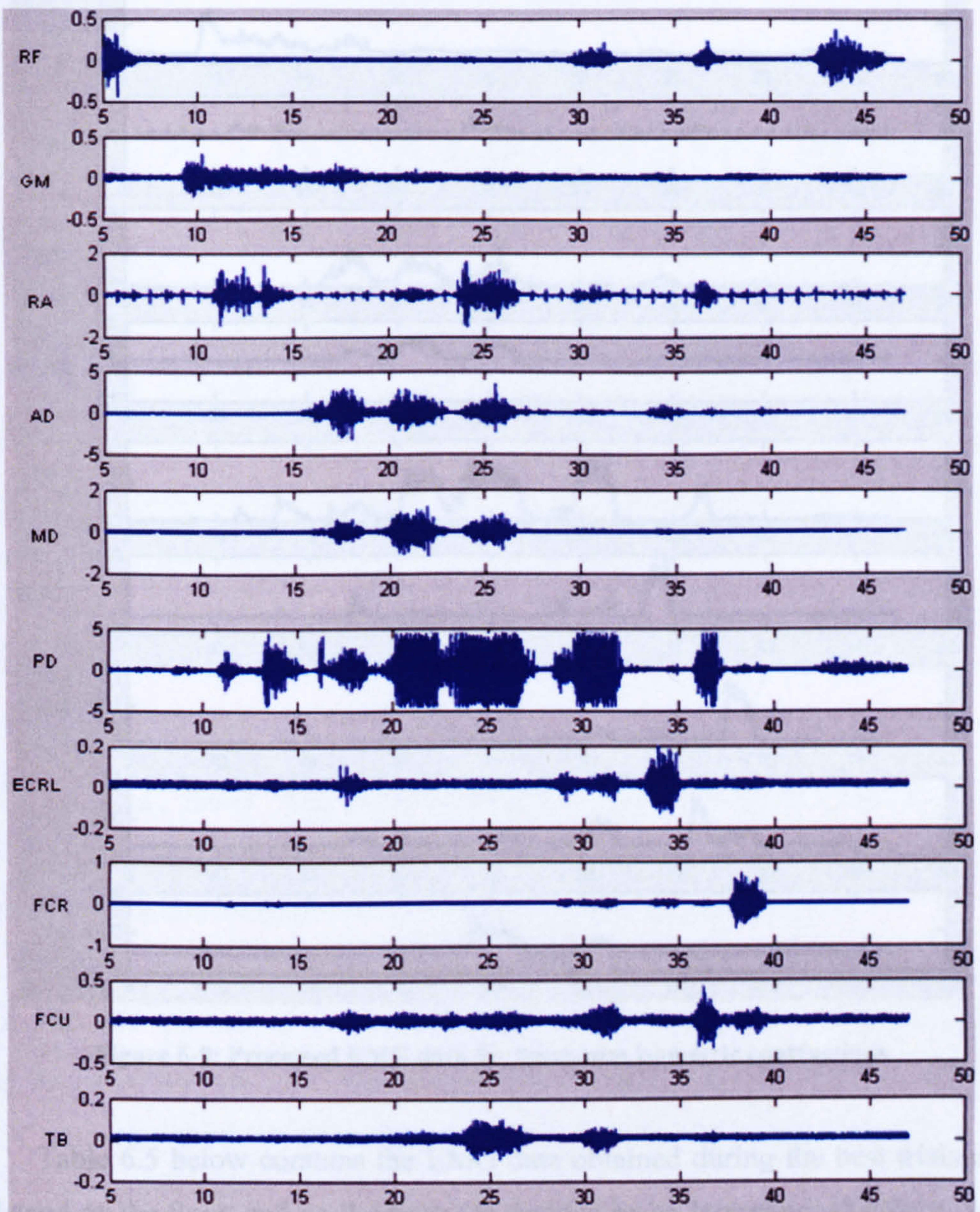


Figure 6-8: Raw EMG data for maximum isometric contractions.

As described in Chapter 4, the raw EMG data was processed before being analysed. The processing involved the data being square wave rectified, and then passed through a low pass filter at 8Hz, as this was found to best reduce the effects of noise.

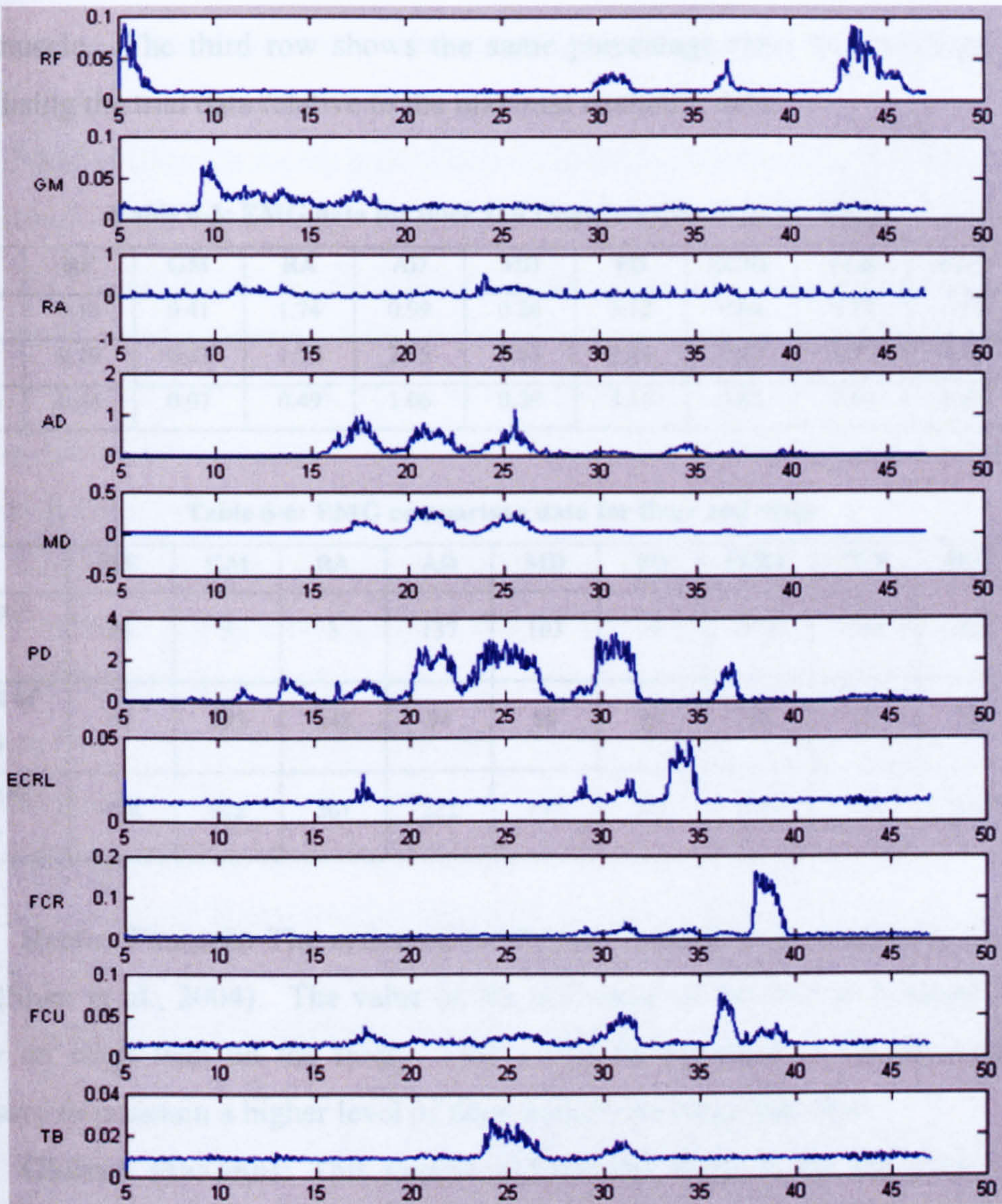


Figure 6-9: Processed EMG data for maximum isometric contractions.

Table 6.5 below contains the EMG data obtained during the best trials of the handstand on the floor, and on the rings (as decided by an International Judge). It also details the EMG value of the corresponding muscles during a maximum isometric contraction, performed by gymnast R. Table 6.6 details the relationship between the magnitudes of the peak EMG values measured during the floor trial and the rings trial. The maximum peak EMG value was used as a method of comparisons between trials, and as a measure of the single largest signal of the whole trial. If the data from a single trial was averaged, it would not give an accurate account of what had taken place. The first row contains the percentage by which the rings trial peak EMG values are larger than the floor trial peak EMG values. The second row contains the percentage ratio of the floor peak EMG values to the maximal isometric values for

each muscle. The third row shows the same percentage ratio for the rings, hence normalising the trial data relative to the maximal isometric data.

Table 6-5: EMG data for floor and rings (maximum peak values)

	RF	GM	RA	AD	MD	PD	ECRL	FCR	FCU	TB
Floor	0.13	0.41	1.74	0.99	0.26	3.12	0.04	0.14	0.09	0.03
Rings	0.19	0.43	1.79	2.35	0.53	2.84	0.43	0.37	0.38	0.41
Max iso	0.14	0.07	0.49	1.06	0.29	3.16	0.05	0.16	0.08	0.03

Table 6-6: EMG comparison data for floor and rings

	RF	GM	RA	AD	MD	PD	ECRL	FCR	FCU	TB
% Rings > Floor	46	5	3	137	103	-9	975	164	322	1267
Floor % of Max iso	91	593	348	94	86	99	94	86	122	90
Ring % of max iso	128	622	361	222	177	90	936	231	506	1484

Rectus Femoris: The action of the Rectus Femoris is to extend the leg at the knee (Shier et al., 2004). The value of the activation of the Rectus Femoris is 46% higher on rings than on the floor. This would be expected as on the rings it is necessary to maintain a higher level of body tension on rings than floor

Gluteus Maximus: This muscle extends the thigh at the hip (Shier et al., 2004). As like the Rectus Femoris, the gluteus Maximus has a higher activation during the handstand on the rings, than it does during the performance on the floor. Though only 5% higher on rings, there is still a possible indication of a greater body tensions during this skill.

Rectus Abdominus: The Rectus Abdominus tenses the abdominal wall and flexes the vertebral column (Shier et al., 2004). A 3% higher EMG value for the handstand on the rings compared to the performance on the floor can once again be explained by the greater requirement of body tension during the more complex skill, however such a low level of difference may be due to signal inconsistency.

Anterior Deltoid: This muscle is recruited for abduction (closing arms together under loading), flexion, and extension, (Shier et al., 2004) consequently the muscle will be engaged to stabilise the shoulder joint position on the rings as there is no friction to maintain the position of the hands like there is on the floor. The EMG reading for this muscle was 137% higher on rings than it was on the floor. As flexion (opening shoulder angle) and extension (closing the shoulder angle) will be used to

reposition hands under the centre of mass, every time the shoulder angle changes, the Anterior Deltoid will be in use.

Medial Deltoid: As the medial deltoid controls abduction, and as this action is not required during the control of a handstand on the floor, there is a 103% increase in medial deltoid activity during the balance on the rings as a comparison to the balance on the floor. Medial rotation, internal rotary movement around the longitudinal axis of the bone towards the centre of the body (turning upper arm inward) for example, twisting hands inward whilst in handstand, will be much lower when performing on the floor as there is friction

Posterior Deltoid: The posterior deltoid is used for abduction, extension, and lateral rotation – that is turning upper arm outward, and so is assumed to be high during both performances. The muscle activation during the balance on the rings was 9% lower than when on the floor. The peak EMG value for the floor may be high due to extension controlling the movement of handstand as shoulder closes to maintain balance (Yeadon 2003). However the value for the rings will also be high due to the use of extension and lateral rotation during the control. It may even be expected that this value would have been higher than on the floor.

Extensor Carpi Radialis Longus: As this muscle extends the wrist and abducts the hand (turns it out), (Shier et al., 2004) it will be used to stabilise the wrist on rings. The activation of the wrist flexors and extensors were all considerably higher for the handstand on the rings. This may be due to the muscles co-contracting to stabilise the joint. The Extensor Carpi Radialis Longus EMG was 975% greater than the value for the floor balance.

Flexor Carpi Radialis: The Flexor Carpi Radialis flexes the wrist and abducts the hand (Shier et al., 2004). The value for the rings balance EMG was 164% greater than on the floor.

Flexor Carpi Ulnaris: This muscle flexes wrist, and adducts hand (turns inward). The Flexor Carpi Ulnaris EMG was 322% higher on rings than on the floor. Although the wrist will hardly move during a balance on rings, abduction and adduction will barely take place but the actions will be opposing each other (co-contraction) to stabilise and lock the position of the wrist, hence heavily recruiting the muscles.

During a handstand on the floor, only flexion is used to control the balance, and as a percentage of the maximum isometric (122%), the floor has the Flexor Carpi Radialis as expected is the most highly recruited wrist flexor or extensor.

Triceps Brachii: This muscle is used to extend the forearm at the elbow (Shier et al., 2004), it will therefore be heavily recruited during the rings balance as the elbow needs to be locked tight. As this action is not as crucial on the floor as the floor is stable and easier to balance upon, it is not surprising that the activation of this muscle was 1267% higher on rings than on the floor.

Subject Feedback

During the handstand balance on the floor, due to the dimensions of the rigid wooden platform, the subject felt that his arms were a little close. This can make the balance harder to hold, and may have resulted in the subject having a slightly closed shoulder angle. It is therefore possible that the subject engaged his shoulder muscles more during the trial for either balance control or through co-contraction, than he would during his normal handstand.

The handstand on floor is generally controlled through the wrist (Yeadon, 2003), so it may have been expected that higher EMG peaks at wrist on floor would have been measured rather than on the rings, as was measured during the testing. It appears that the tension required to lock the wrists whilst balancing on rings results in a higher muscle activation than does the wrist control during a still handstand. This may also be due to the fact that the handstand performed on floor was very good and very still although the wrist flexor would have been contracted throughout the skill, there were no large balance corrections made which may result in high EMG readings.

From the EMG trace obtained for the wrist flexors and extensors it can be seen that during the floor balance, the wrist muscles were continually switching on and off to control the balance. The trace is jagged and contains lots of peaks with a steep rise above the average amplitude of the trace (Figure 6.10). This is indicative of muscles which are being used to control or sustain an action or balance (Konrad, 2005).

In contrast, the EMG trace for the handstand on the rings is much smoother, with very few small peaks. The width of the active contraction burst indicates for how long the muscle was 'on'. At frequencies between 8-10Hz, it is assumed that the muscle is experiencing tremor (Cussons et al., 1980; Farmer, 1999). Muscle tremor generally occurs during sustained high muscle activation, and is described as minute movement steps which are achieved through pulsating agonist-antagonist activity (Farmer, 1999). This confirms that although the wrist is more active during the rings balance, they do not change position.

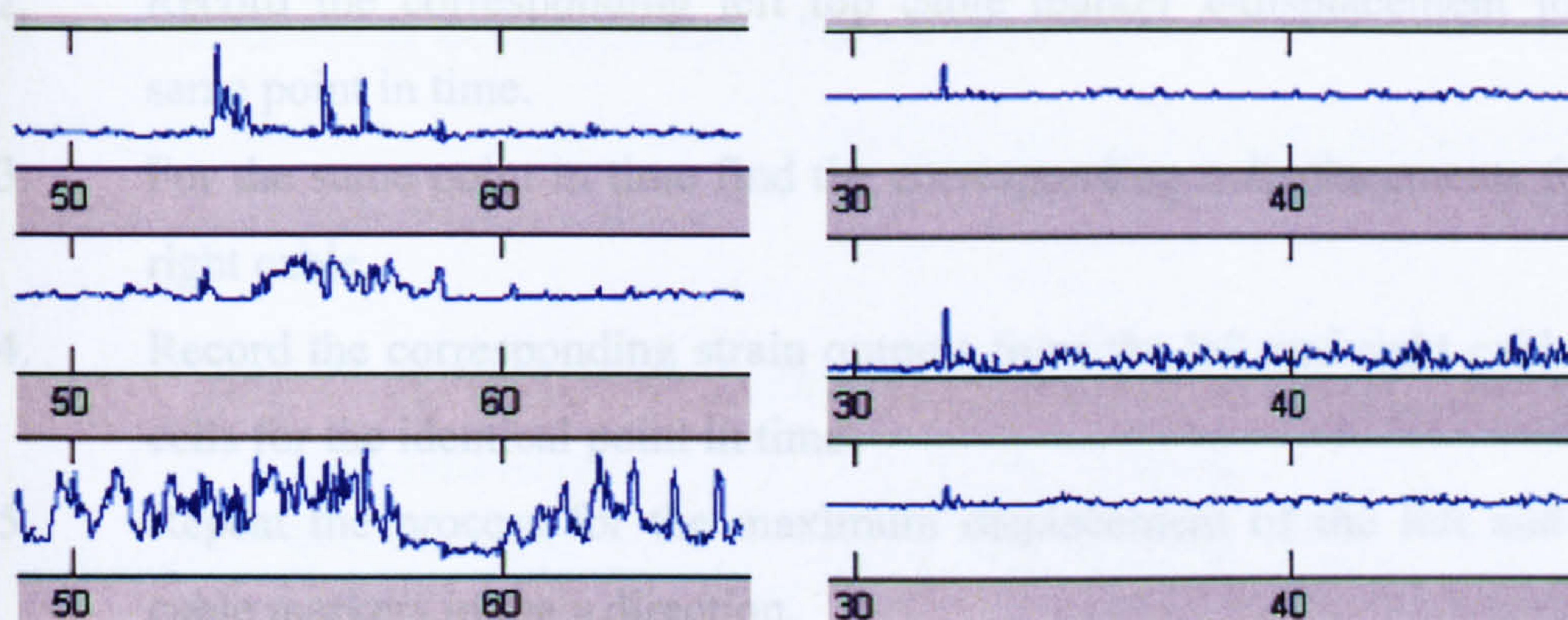


Figure 6-10: Processed EMG data - Left: Floor wrist EMG; Right: Rings wrist EMG.

6.4.3 Force and strain data

Before any data was obtained on performances, the load cells were re-calibrated using the same method discussed in Chapter 4. Incremental loads were hung on the rings, and a strain-load relationship was established for each strain gauge (Figure 6.11).

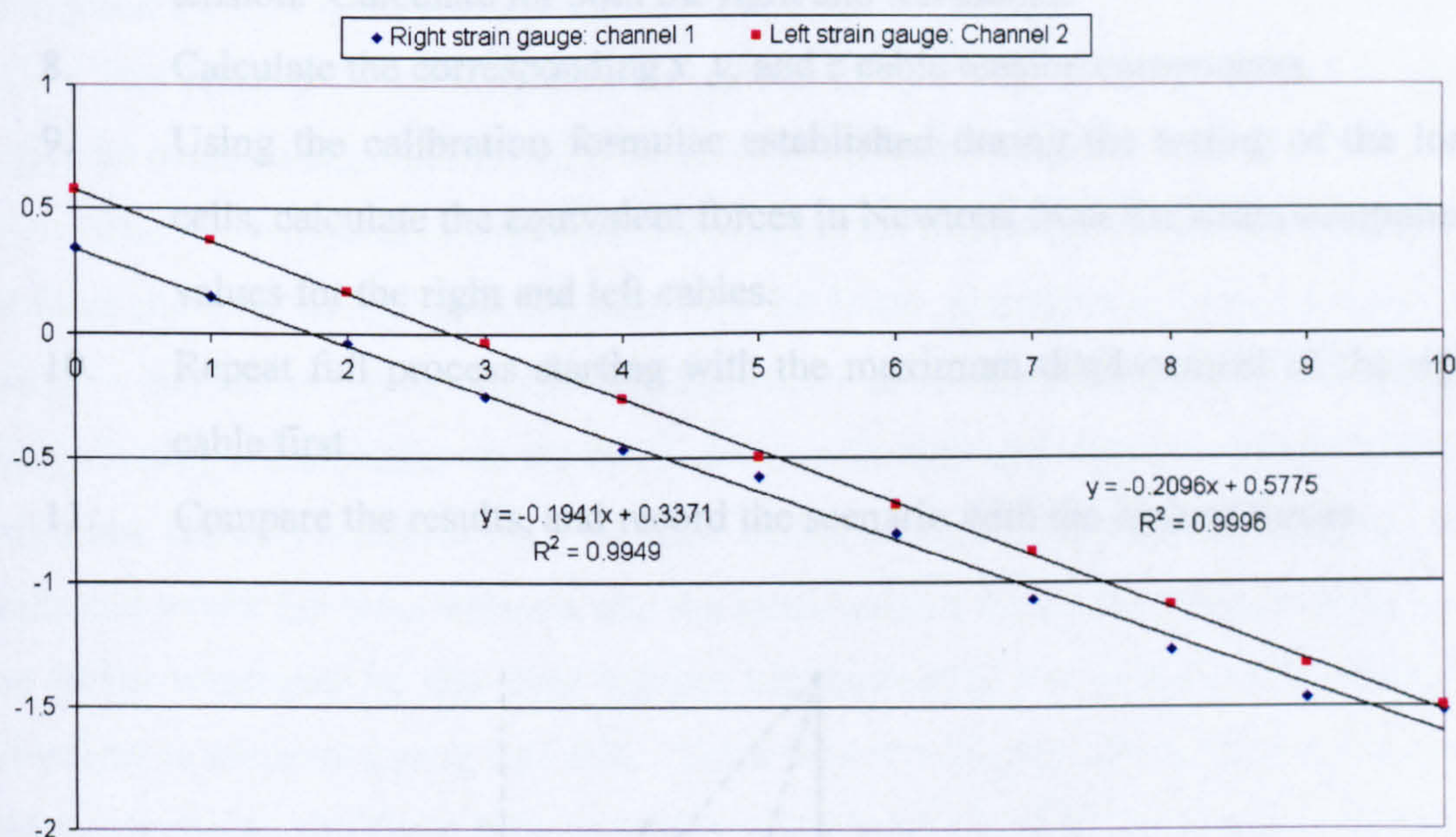


Figure 6-11: Strain gauge calibration equations and graph
(Right gauge S.E = 0.250; Left gauge S.E = 0.067).

From the strain data obtained from the cables, the horizontal and vertical components of force were calculated as follows:

1. Record the maximum left bottom cable marker displacement in the x direction (back and forth) as this is the primary movement, and the corresponding time.

2. Record the corresponding left top cable marker x -displacement for the same point in time.
3. For the same point in time find the corresponding x -displacements for the right cable.
4. Record the corresponding strain outputs from the left and right cable load cells for the identical point in time.
5. Repeat the process for the maximum displacement of the left and right cable markers in the y direction.
6. $x = x_m - x_l$, where x_m is the maximum displacement of the bottom cable marker in the x direction minus the top cable marker position in the x direction. Similarly: $y = y_m - y_l$, and $z = z_l - z_m$, (see Figure 6.12).
7. Manipulation of the 3-D co-ordinate system allows the strain to be broken down into its three co-ordinate constituents, T_x , T_y and T_z :

$$T_x = \frac{x}{r}T, \quad T_y = \frac{y}{r}T \quad \text{and} \quad T_z = \frac{z}{r}T, \quad \text{where } r^2 = x^2 + y^2 + z^2 \quad \text{and } T = \text{cable tension.}$$
 Calculate for both the right and left cables.
8. Calculate the corresponding x , y , and z cable tension components.
9. Using the calibration formulae established during the testing of the load cells, calculate the equivalent forces in Newtons from the strain component values for the right and left cables.
10. Repeat full process starting with the maximum displacement of the right cable first.
11. Compare the results, and record the scenario with the highest forces.

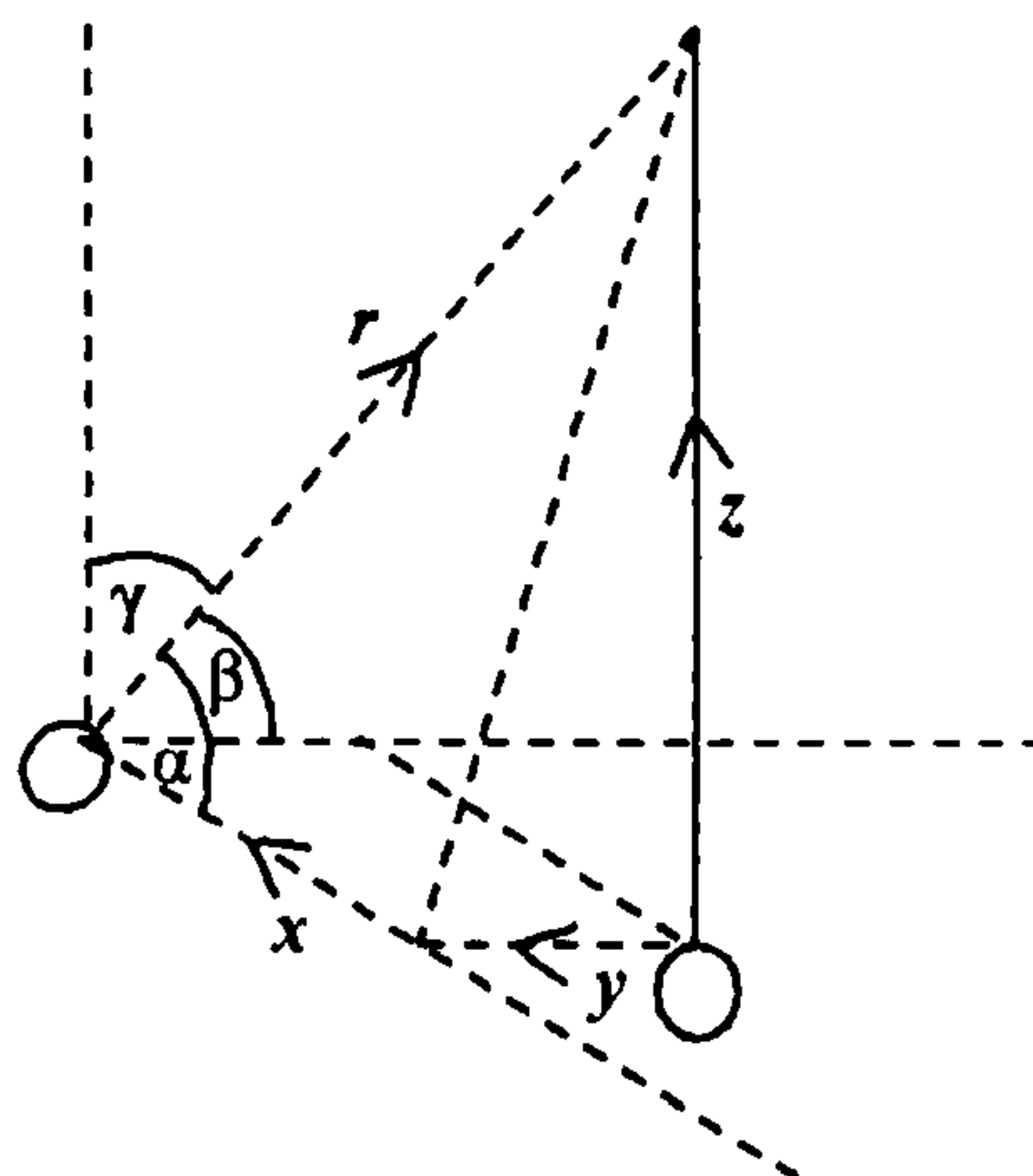


Figure 6-12: 3-D co-ordinate system for cable strain.

6.4.4 Handstand comparison - force results

The calculated force components for the floor and rings have been compiled and recorded in Table 6.7 below:

Table 6-7: Horizontal force data for handstand on floor and rings

Horizontal forces	F_x (N)	F_y (N)
Floor Handstand	32	19.8
<i>Left cable maximum</i>		
Rings Handstand Left cable	27.4	1.7
Rings Handstand Right cable	50.1	33.1
<i>Right cable maximum</i>		
Rings Handstand Left cable	27.3	17.3
Rings Handstand Right cable	48.9	36.3

Using the maximum resultant forces for the rings cables: The F_x horizontal forces (back and forth) for the right and left rings would be added together by the force plate: $F_x = 27.4 + 50.1 = 77.5\text{N}$.

The value of F_y horizontal forces (side to side) would in fact cancel each other to give an overall magnitude of: $F_y = 33.1 - 1.7 = 31.4\text{N}$.

The forces measured from the rings cables are higher than those obtained from the force plate for the handstand balance on the floor. Considering Newton's second Law, $F = ma$, if the wrists are moving then there is acceleration therefore there is a force. During a handstand on the floor, there is friction and therefore the horizontal forces are resistive forces. As the mass centre does not move very much as the handstand would fall from balance, and the hands cannot move, the forces remain low. The forces measured for the floor balance are especially low sideways as sideways movement is minimal during this skill. There will also be postural sway forwards and backwards during the floor balance which will create a higher force back and forth, but this will still be relatively low compared to the rings due to only comparatively small movements of the mass centre.

Any training aid designed to help learn a handstand on the rings should have no friction like the real environment. The horizontal forces created whilst on the rings are due to the horizontal component of the cable tension. Cable tension is increased by the movements of rings under the loading of the mass centre. Cable tension is a function of the position of the mass centre: the smaller the angle between the mass centre and the cable, the greater the loading. On rings the mass centre does not move

very much unless the handstand swings, therefore it is not the movement of the mass centre which creates the horizontal forces. It is the movement of the rings (wrist) under the loading of the mass centre which creates the forces. As the rings move further away from the mass centre, a greater angle is produced between the suspension point and the bottom of the rings cable, and this increases the horizontal component of the cable tension. As $F = ma$, and fast 'jerky' movements have higher accelerations than slower smooth movements, the more vigorous the movement of the wrist is the bigger the forces are, and consequentially a perfect handstand on rings would have lower forces than a poor one.

The rings cables create disturbances to balance as they have a restoring force bringing the rings back to a vertical position. The developed training aid does not. Without the restoring force, when significant balance controlling movements are required a 'drift' of body position can occur. This is due to the gymnast correcting his position to retain balance, and in doing so repositions his mass centre slightly away from the centre of the training aid. Continual corrections result in the body moving further away from the centre of the training aid, which on the rings would have induced a quantity of swing.

It was observed during the study, that gymnast R found it easier to balance the handstand on the training aid than on the rings, as with corrective movements the gymnast could retain a still stance. This is not always possible on the rings even with a perfect handstand as swing may have been induced during the entry into the skill. On the training aid the gymnast is only balancing the handstand, whereas the rings have the continual restoring force, necessitating the gymnast to balance any cable swing as well as the handstand.

From the customer requirements established in Chapter 3, it was stated that for the training aid to succeed, it should simplify learning, and be easier to perform a handstand on than the rings. Therefore the fact that the training aid does not involve cable swing, hence allowing the gymnast to balance only the handstand is a fulfilment of this customer requirement.

6.4.5 Motion analysis data

Motion data was collected in the form of Vicon marker displacement data and digital video images of the skills being performed. The Vicon data was processed to give various motion parameters. Raw Vicon marker displacement data (in units of

millimetres) was corrected with respect to measured joint centre offsets. This produced displacement data for the movement of the individual joint centres (in the units of metres). Subject anthropometric data was then used with the joint centre locations to calculate the movement of the mass centre, the somersault angle produced during the control and the tilt of the skill during the performance.

6.4.6 Handstand comparison – motion analysis results

The data collected and analysed will be discussed separately in order to permit an easy comparison of the two skills. Graphs of the joint centre movement for each of the nine trials can be found in Appendix E.

Vicon

The handstand on the rings was not observed to have any significant swing, (unlike in Chapter 4) therefore the magnitude of the cable swing was measured to establish if the displacement data needed filtering before analysis. During the trials, markers were positioned at the bottom of the rings cables directly above the wooden ring, thus providing the displacement data of the rings. When considering the actual values of the maximum displacement in the x direction (back and forth) of the rings markers, it was found that: the left bottom marker = $391 - 133 = 258\text{mm}$; which equals only a 129mm movement of the left ring in each direction. The right bottom marker = $395 - 146 = 249\text{mm}$; which equals only a 124.5mm movement of the right ring in each direction.

Movement of only 129mm does not represent significant swing, as this movement will have been mainly caused by the continual correction of balance during the performance of the skill. Therefore the data was not filtered, so that movement data was not lost. Any effects that minor quantities of swing present in the data may have had on the performances will be discussed in the following sections.

Joint Centre Movement and Joint Angles

The main joint centres which are of interest are the wrist, shoulder, hip and toe. From these few parameters, the configuration of the body, shoulder angle and hip angle can be established. From the joint centre displacement (Figure 6.13) it was easy to deduce that the handstand performed on the floor was a particularly still handstand.

The magnitude of the movement measured for the handstand on the floor: Wrist = 0.0015m; shoulder = 0.0003m; hip = 0.0237m; toe = 0.1186m.

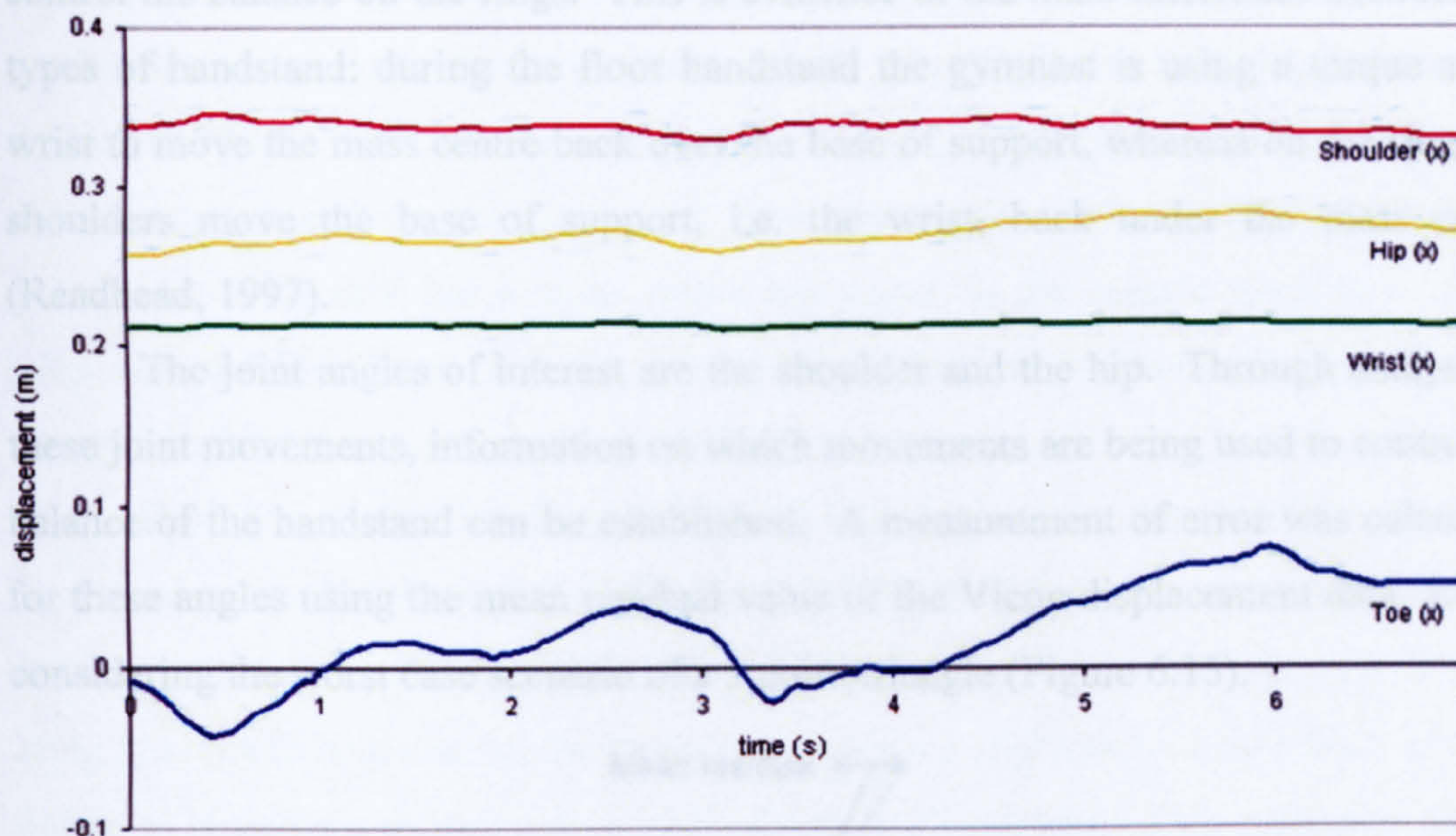


Figure 6-13: Subject R, floor handstand joint centre data (scale in metres).

The same measurements for the rings (Figure 6.14) were: Wrist = 0.2637m, this will however be larger than expected due to the slight swing; shoulders = 0.1573m, gymnast will have attempted to keep his shoulder still during the balance; hips = 0.1724m, and the toes = 0.4808m, the magnitudes of movement for the toes is greater than the hips. For this to occur the gymnast must have been actively opening and closing his hip angle whilst attempting to maintain the balance.

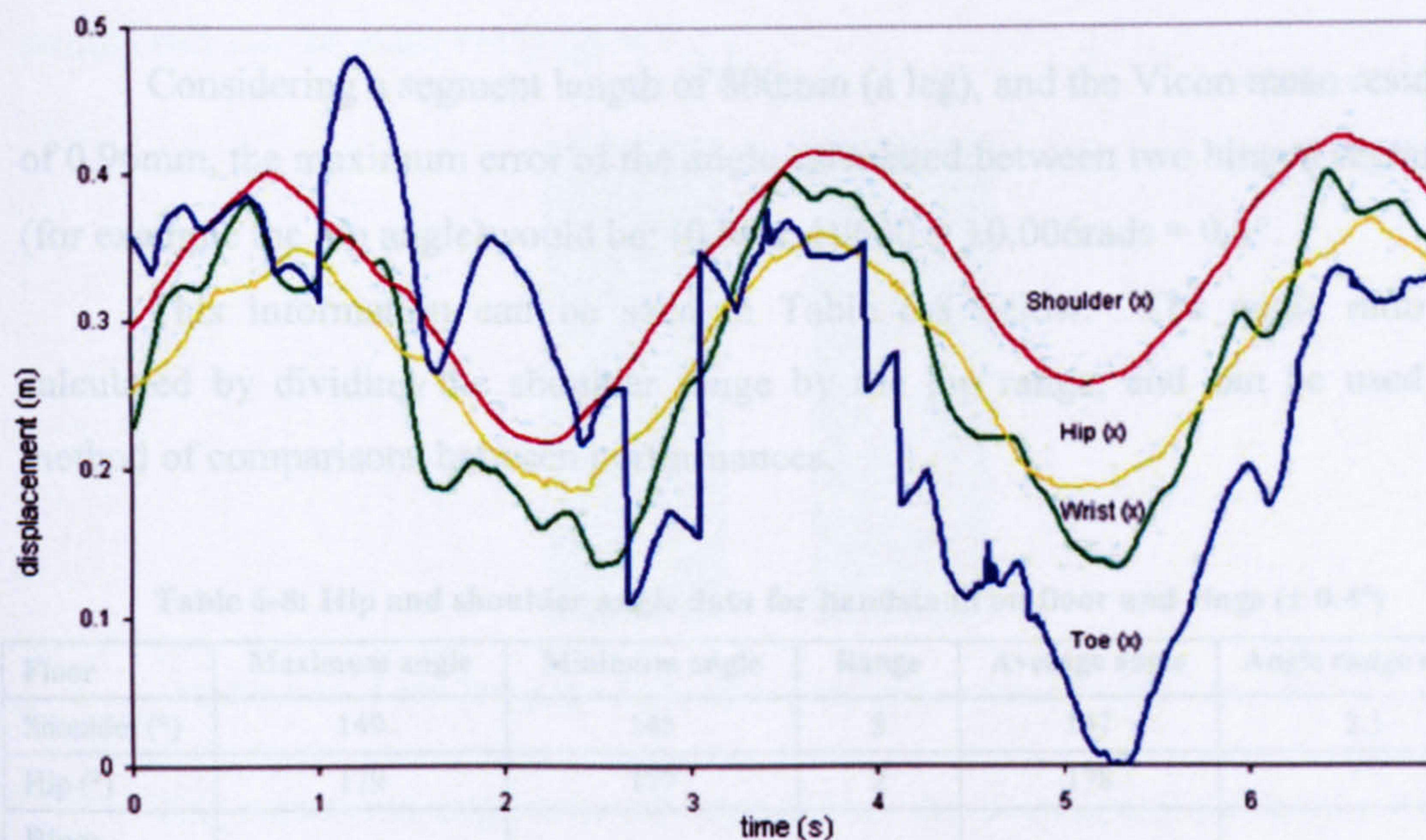


Figure 6-14: Subject R, rings handstand joint centre data.

As the wrists move more than the shoulders, and the toes move more than the hips, the data suggests that the gymnast was using both his shoulder and hip angle to control his balance on the rings. This is evidence of the main difference between the types of handstand: during the floor handstand the gymnast is using a torque at the wrist to move the mass centre back over the base of support, whereas on the rings the shoulders move the base of support, i.e. the wrist, back under the mass centre (Readhead, 1997).

The joint angles of interest are the shoulder and the hip. Through analysis of these joint movements, information on which movements are being used to control the balance of the handstand can be established. A measurement of error was calculated for these angles using the mean residual value of the Vicon displacement data, and by considering the worst case scenario of a 3 point triangle (Figure 6.15).

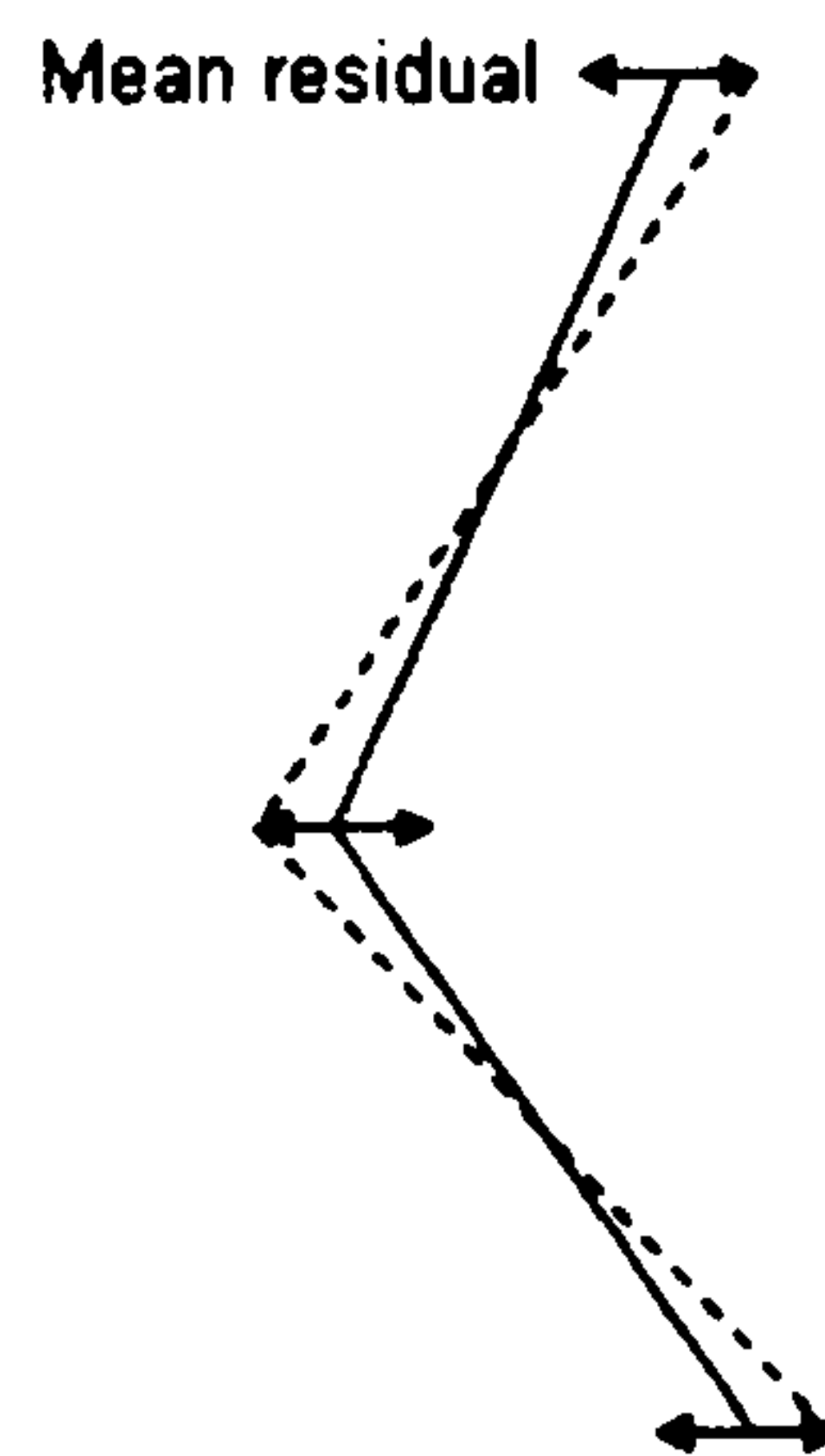


Figure 6-15: Calculation for joint angle error.

Considering a segment length of 800mm (a leg), and the Vicon mean residual of 0.96mm, the maximum error of the angle calculated between two hinged segments (for example the hip angle) would be: $(0.96 \times 4)/600 = \pm 0.006 \text{ rads} = 0.4^\circ$.

This information can be seen in Table 6.8 below. The angle ratio was calculated by dividing the shoulder range by the hip range, and can be used as a method of comparisons between performances.

Table 6-8: Hip and shoulder angle data for handstand on floor and rings ($\pm 0.4^\circ$)

Floor	Maximum angle	Minimum angle	Range	Average angle	Angle range ratio
Shoulder ($^\circ$)	149	145	5	147	2.1
Hip ($^\circ$)	179	177	2	178	
Rings					
Shoulder ($^\circ$)	154	141	13	147	0.6
Hip ($^\circ$)	178	157	22	167	

As can be seen in the information above, as expected, the range of movement in the hip and shoulder angle is minimal in the floor handstand (Yeadon, 2003), with the majority of the movement coming from the shoulder rather than the hip. During the handstand on rings, the movement in both joint angles is much higher than the skill on the floor. This is to be expected due to the quantity of movement experienced during a handstand on the rings, and also due to the method of controlling that movement. This skill has a more closed hip angle, as the subject maintains a more solid dished body shape, and the control of the balance is occurring slightly more through the hips than through the shoulders.

During a perfect handstand you would expect to see the majority of a rings handstand controlled through the movement of the shoulders. However as the subject demonstrates large variations in the hip angle, it is possible that the gymnast is either using his hips to help control the balance, or he has a slight lack of mid-body strength and so is struggling to maintain a stable body configuration. This particular trait of hip angle variation must also be seen during performances on the training aids if they are to be compared to the performance on the rings.

Mass centre Movement and Mass Centre – Wrist Relationship

To find out what the methods of control for the different handstands are, the position and movement of the mass centre must be compared relative to the wrist. The difference in position of the mass centre relative to the wrist will be compared, and the somersault angle (the angle between the centre of the wrist and the mass centre) will also be analysed (Figure 6.16).

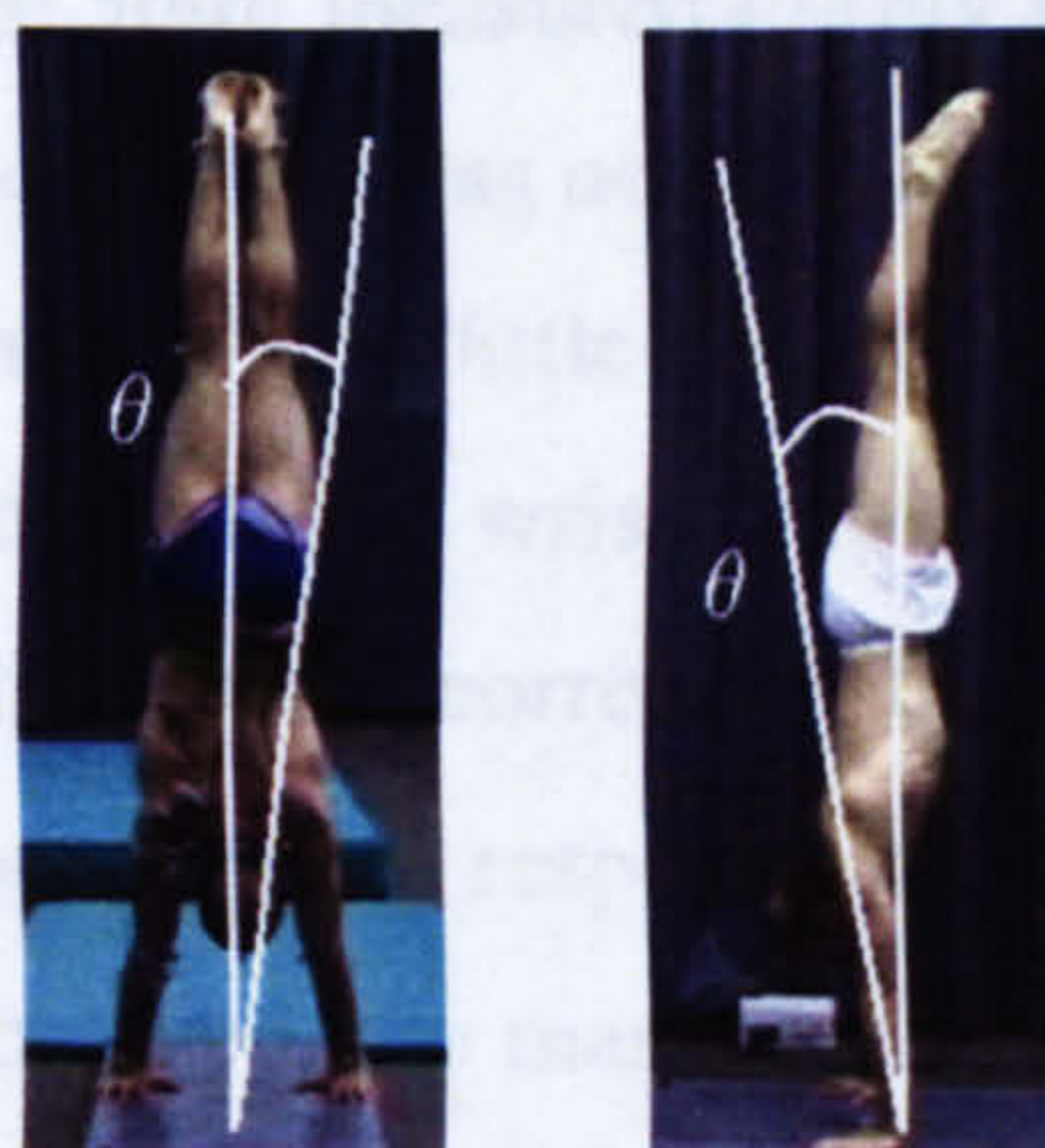


Figure 6-16: Left: Tilt angle description; Right: Somersault angle description.

The somersault angle was calculated from the wrist centre position minus the position of the mass centre back and forth. This parameter was positive when the handstand was leaning over hands. Tilt was calculated from the difference between

the position of the wrist centre and the mass centre sideways, where right is positive. The data analysed was compiled (Table 6.9) below:

Table 6-9: Mass centre movement data (displacement ± 1 mm, angle $\pm 0.4^\circ$)

Floor	Max position	Min position	Range (m)	Average position
Mass centre x	0.29	0.27	0.02	0.28
Mass centre y	0.21	0.20	0.01	0.21
Wrist x	0.21	0.21	0.01	0.21
Wrist y	0.21	0.20	0.00	0.20
Mass centre – wrist (x)	0.08	0.06	0.02	0.07
Mass centre – wrist (y)	0.01	0.00	0.01	0.00
Somersault angle ($^\circ$)	5	4	1	5
Tilt ($^\circ$)	1	0	1	0
Ring	Max position	Min position	Range (m)	Average position
Mass centre x	0.39	0.21	0.18	0.30
Mass centre y	0.26	0.21	0.05	0.23
Wrist x	0.39	0.13	0.26	0.26
Wrist y	0.24	0.19	0.05	0.21
Mass centre – wrist (x)	0.09	0.00	0.09	0.05
Mass centre – wrist (y)	0.03	0.01	0.02	0.02
Somersault angle ($^\circ$)	6	-1	7	3
Tilt ($^\circ$)	2	1	2	1

During the handstand on the floor, the mass centre moved approximately 10mm in the y direction (sideways), and moves 20mm in the x direction (back and forth). Even when the handstand was still, during any control which takes place, the mass centre moves back over the hands, with practically no movement from the wrist. It was expected that there should be no movement measured from the wrists as the hands did not move, and so the 5mm measured during the trial will most probably be due to marker movement as the marker was not precisely over the joint centre. During this balance, the mass centre moved very little in either direction.

During the rings handstand the wrists moved more than the mass centre, especially back and forth as they were correcting the balance. The minimal swing described earlier may have been partly responsible for the movement of the mass centre on rings. In a perfect balance, the mass centre should not move very much at all. During the rings performance the mass centre moved 178mm back and forth. However the wrist moved 264mm in the same direction, showing that the shoulder control technique was being used.

The distance between the mass centre and wrist during the floor handstand only ever reached a maximum of 20mm in the x direction and 9mm in the y direction,

and the somersault angle covered only a range of 1° , as the balance was so still. The average somersault angle was 5° , which provides the information that the mass centre was over the middle of the hands, where it is expected to be. There was practically no tilt present during this handstand.

On the rings, the distance between the mass centre and the wrist movement was 23mm in the y direction, as practically no movement occurs side to side during a handstand on rings. The range of movement in the x direction was measured to be 99mm, as the wrist move back and forth beneath the mass centre to balance the skill.

As the somersault angle was dependant on wrist and mass centre movement, the rings handstand had a much a bigger somersault angle than the floor balance. The somersault of the rings was calculated to cover a range of 7° , with an average position of 3° . This orientation has the mass centre positioned further back towards the wrist than on the floor. This is expected as the hands are turned out 90° along the longitudinal axis of the forearm, moving the mass centre to much closer to the joint centre. The tilt was only just over a degree and so was not considered significant.

6.4.7 Summary of comparison

- The rings handstand produces a higher EMG reading for muscles which control body tension.
- The arms were used much more in the handstand on the rings than on the floor.
- The handstand on the rings produced larger wrist EMG readings than the performance on the floor, but the floor trace showed large muscle contractions as the muscles switched on and off, whereas although the overall activation was higher during the rings handstand, only muscle tremor was observed within the trace.
- Forces were measured to be higher on the rings than on the floor.
- There was substantially more joint centre movement during the rings handstand than was measured during the floor handstand.
- The average shoulder angle was very similar during the two performances.
- The hip angle was more open during the handstand on the floor.
- The control strategy was shown to use the wrist during the floor balance, and was shown to use the shoulder and possibly the hip during the rings balance.
- Movement of the wrist was minimal on the floor, and large on the rings.

- Both performances had insignificant sideways movement of the mass centre, the movements back and forth of the mass centre during the rings balance was almost ten times larger than on the floor.
- The range of movement back and forth between the position of the mass centre and the wrist joint centre was very small on the floor, and was 99mm during the performance on the rings.
- The somersault angle during the handstand on the rings positioned the centre of mass over the centre of the hands, with an angle of 5°. During the rings balance, the somersault angle was measured to be 3°, also with the mass centre over positioned over the centre of the wrist (hands in a rings grip).

6.5 Training aid details

The following section will contain a brief description of each training aid, and will detail the position of the Vicon markers used during the data collection.

6.5.1 The handstand swing

The handstand swing (Figure 6.17) was a metal rocking structure, upon which the gymnast performed a handstand balance. For the data collection, Vicon markers were positioned at the four corners of the equipment. The equipment will be referred to as the 'rocker' as a descriptive abbreviation.

6.5.2 The handstand bowls

The handstand bowls (Figure 6.18) were two separate hemispherical metal bowls, with wooden dowels attached across the diameter of each bowl. The gymnast placed a hand on each dowel and performed the handstand balance on top of the two bowls. Four markers were placed on each bowl, 90° apart, with two markers at each end of the dowel.



Figure 6-17: Handstand swing.



Figure 6-18: Handstand bowls.

6.5.3 The handstand rails

Figure 6.19 below, is a picture of the prototype training aid in the final stage of set-up. It has six degrees of freedom as each arm can travel in the x -axis, can travel in the y -axis and rotate in the z -axis.

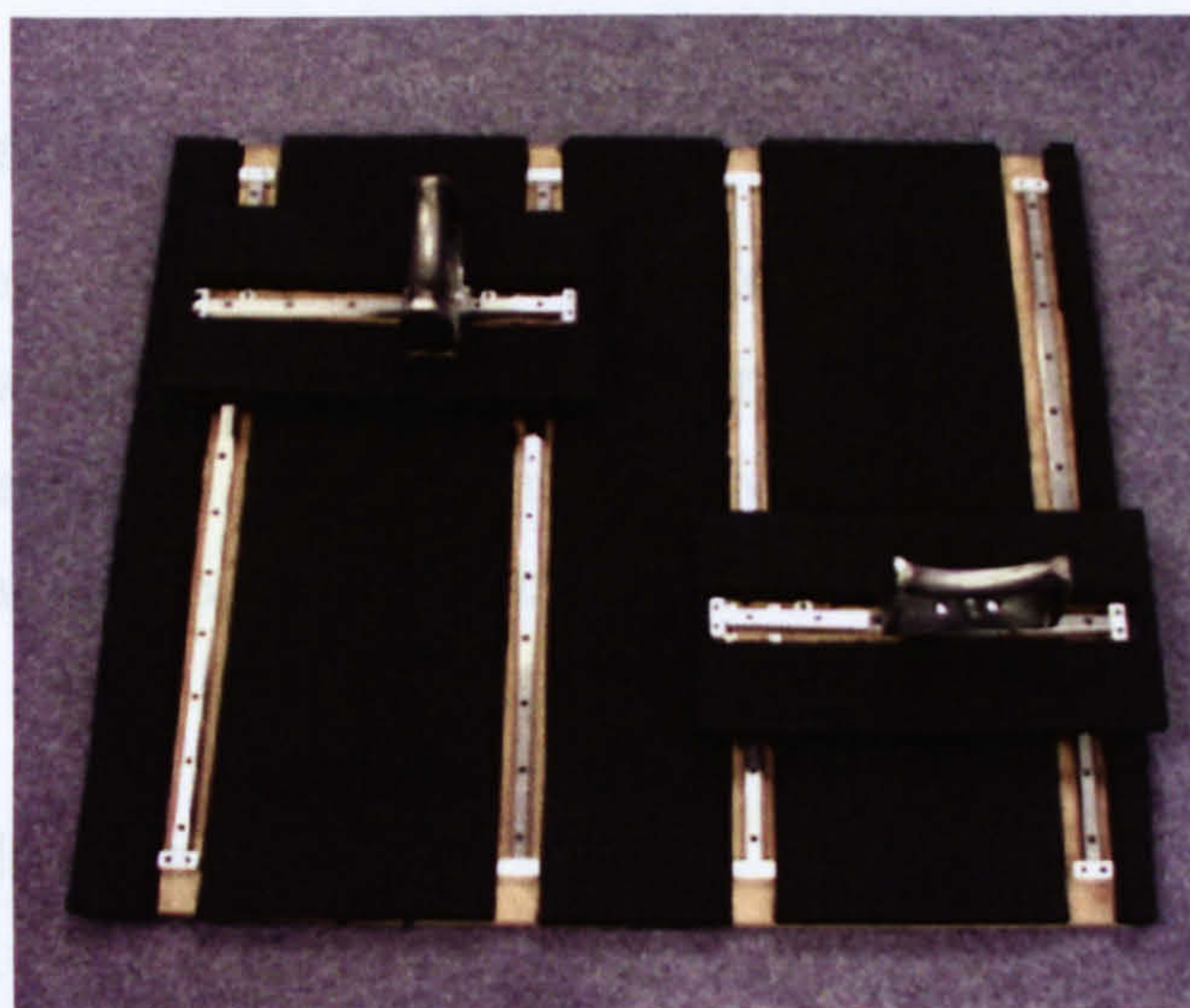


Figure 6-19: Prototype training aid with 6-degrees of freedom.

The prototype training aid was analysed at each of the four possible settings of the training aid, and then a fifth test was performed to ‘mimic’ a novice gymnast using the training aid. Markers were placed on the front and back of each handle.

Rails 1: This was the first setting of the training aid. The arms could not move independently, and the wrists could not rotate. Only a forward and backward action could be used to control the balance (1 degree of freedom).

Rails 2: Releasing the lock between the two hand holds permitted the arms to move independently back and forth. The handles were still locked to prevent rotation of the wrist (2 degrees of freedom).

Rails 3: Releasing the side locks introduced a second dimension of movement. The training aid would now permit motion in both the x and y directions (4 degrees of freedom). The wrists were still prevented from rotating.

Rails 4: The final set-up for the training aid was to release the wrist locks. This would permit the training aid to move forwards, backwards, sideways, and for the handles to rotate round (6 degrees of freedom). This was the same number of degrees of freedom of movement as the rings.

Rails 5: To estimate the performance of a novice gymnast on the training aid, once in balance, the gymnast R was slightly perturbed, making him lose balance, and making him struggle to regain control.

6.6 Data analysis - training aid comparison

The three training aids were each compared to the handstand on the floor, and on the rings. This was to establish which control strategy a performance using the equipment most resembled. The training aids were also compared to each other to establish which was the most effective rings handstand training aid.

6.6.1 Muscle data

This study immediately followed the first, and so the electrodes were not removed from Gymnast R, but the subject was given an adequate rest between performances to prevent the onset of fatigue.

When the amplitudes of the data collected are higher than the maximal isometric data collected, it suggests that the subject was unable to maximally contract the muscles required whilst only under static rather than dynamic loading. There is very little data available on the effectiveness of maximal voluntary contraction positions, and so for the maximal isometric data collected, standard exercises described in Konrad (2005) were followed. Although the performance EMG had a greater magnitude than the data collected during the maximal isometric contractions, the data was still useful as it provided a datum to which all trials could then be compared.

6.6.2 Training aid comparison - EMG results

For the training aid to be classed as successful it was necessary for the gymnast to recruit the same muscles, and by similar proportions to the performance on the rings. This would demonstrate that the control technique has been similar. The required data was obtained, and compiled into Table 6.10 below.

Table 6-10: EMG data for all trials

	RF	GM	RA	AD	MD	PD	ECRL	FCR	FCU	TB
Floor	0.13	0.41	1.74	0.99	0.26	3.12	0.04	0.14	0.09	0.03
Rings	0.18	0.43	1.80	2.35	0.53	2.84	0.43	0.37	0.38	0.41
Rocker	0.06	0.38	0.68	1.46	0.30	0.35	0.10	0.09	0.09	0.04
Bowls	0.09	0.49	1.21	1.50	0.30	2.85	0.08	0.07	0.11	0.09
Rails 1	0.25	0.73	0.53	1.40	0.30	3.09	0.17	0.59	0.42	0.13
Rails 2	0.40	0.66	0.74	1.88	0.36	3.16	0.22	0.59	0.44	0.18
Rails 3	0.30	0.86	1.66	1.55	0.38	2.98	0.14	0.14	0.14	0.11
Rails 4	0.35	0.67	1.75	1.67	0.30	2.47	0.11	0.13	0.13	0.02
Rails 5	0.33	0.13	0.47	0.94	1.47	0.32	2.87	0.13	0.15	0.35
Max Iso	0.14	0.07	0.50	1.06	0.30	3.16	0.05	0.16	0.07	0.03

Figure 6-20: Graph of training aid EMG data as a percentage of the class EMG data.

The data were then graphed to give a visual comparison between the trials (Figure 6.20).

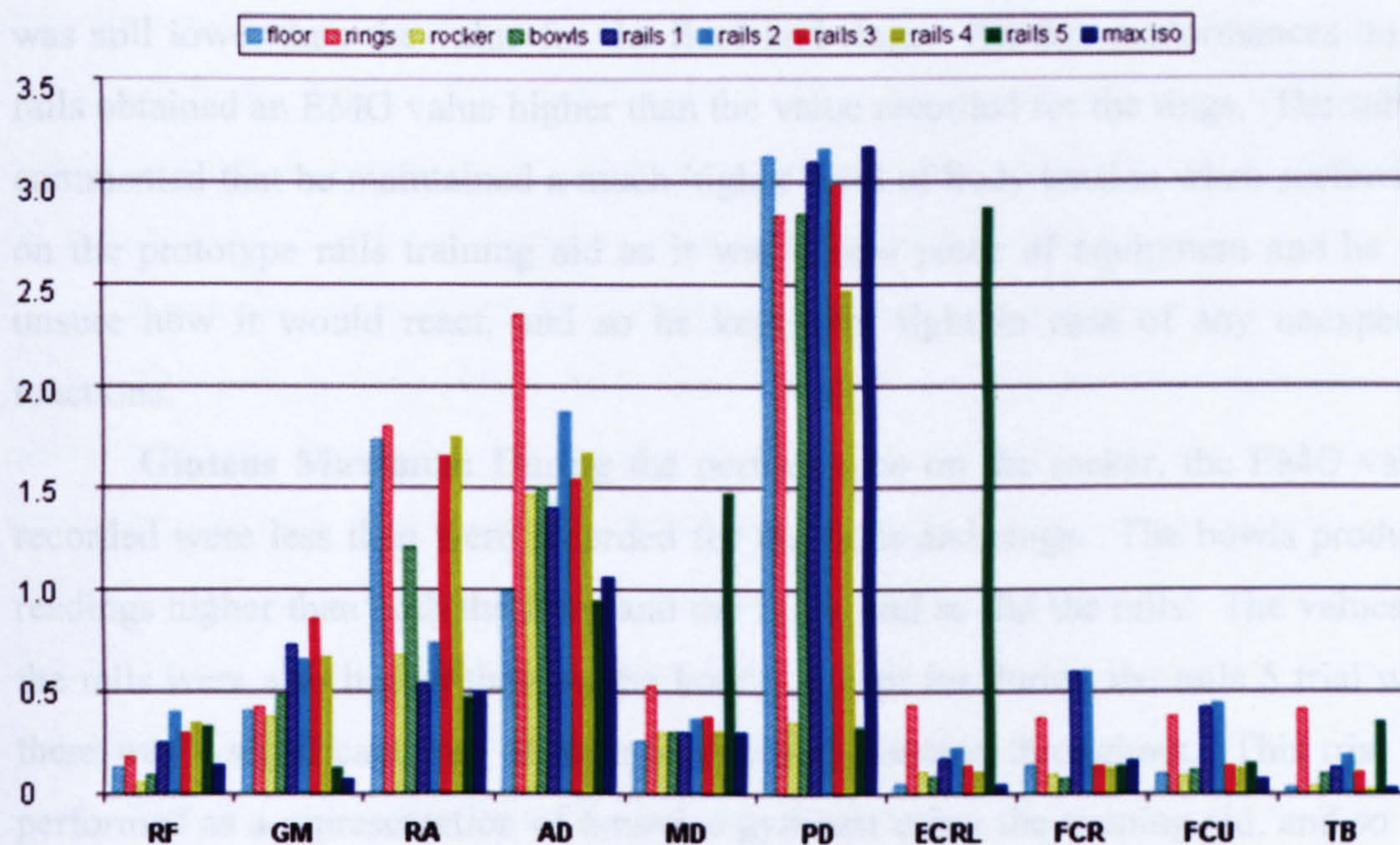


Figure 6-20: Muscle activation data for all handstand trials.

To directly compare the EMG data from the training aids to that of the rings, the training EMG values were divided by the values obtained from the rings to produce a percentage relationship (Figure 6.21).

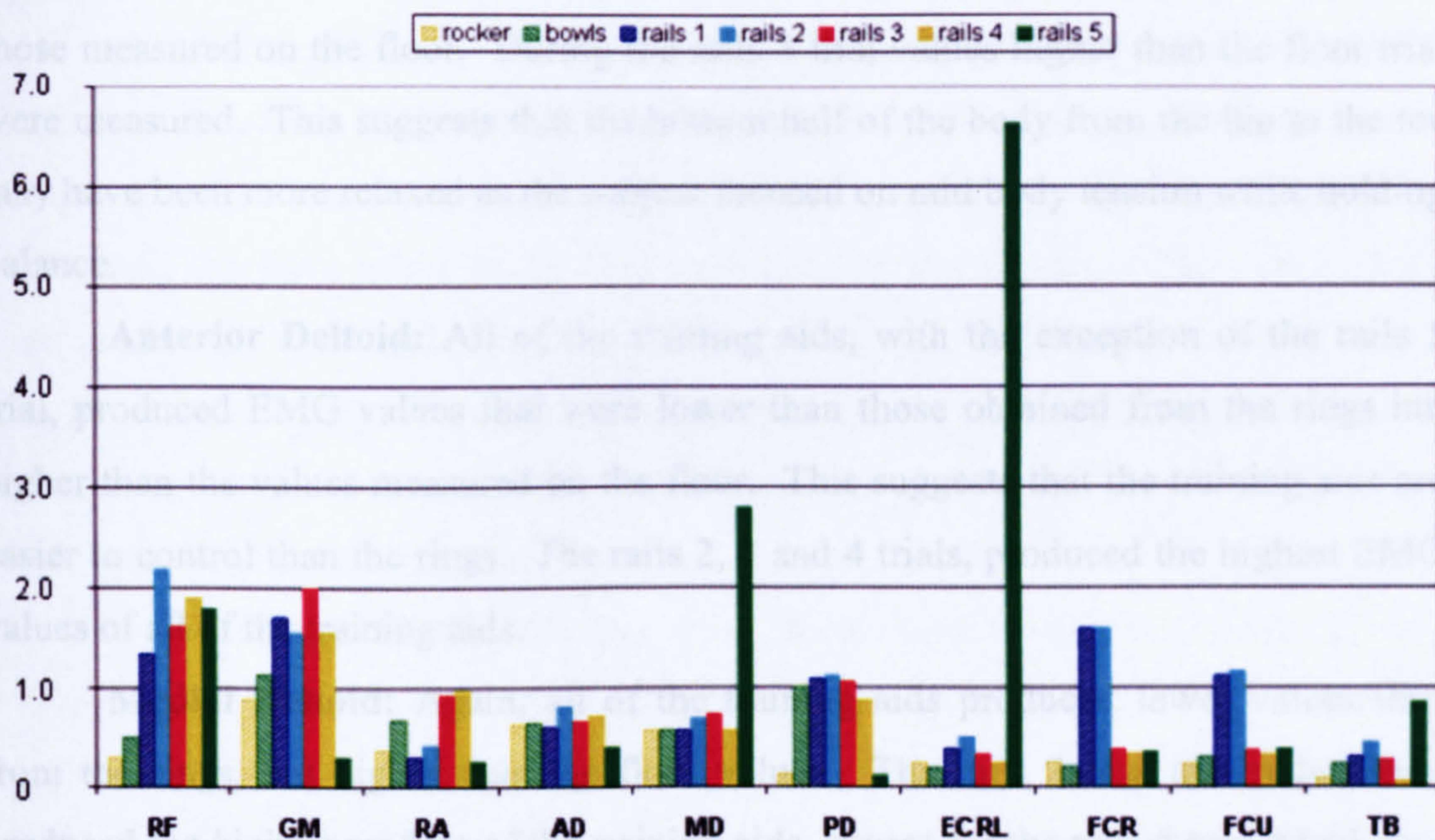


Figure 6-21: Graph of training aid EMG data as a percentage of the rings EMG data.

Rectus Femoris: The value of the EMG for the rocker was less than the value from the rings and the floor. The bowls obtained a higher value than the rocker, but it was still lower than the value for the floor and rings. All five performances on the rails obtained an EMG value higher than the value recorded for the rings. The subject commented that he maintained a much higher level of body tension when performing on the prototype rails training aid as it was a new piece of equipment and he was unsure how it would react, and so he kept very tight in case of any unexpected reactions.

Gluteus Maximus: During the performance on the rocker, the EMG values recorded were less than were recorded for the floor and rings. The bowls produced readings higher than both the floor and the rings, and so did the rails. The values for the rails were also higher than on the bowls, except for during the rails 5 trial when there was a significant loss of balance and body tension throughout. This trial was performed as a representation of a novice gymnast using the training aid, and so will not be included in the general analysis of the training aid.

Rectus Abdominus: The performance on the rocker produced much lower values than on the floor and on the rings. The bowls values were also lower than the floor and rings values. The values obtained from the rails were mainly lower than values obtained on the floor and rings, with the rails 3 trial producing values close to those measured on the floor. During the rails 4 trial values higher than the floor trial were measured. This suggests that the bottom half of the body from the hip to the toe may have been more relaxed as the subject focused on mid body tension while holding balance.

Anterior Deltoid: All of the training aids, with the exception of the rails 5 trial, produced EMG values that were lower than those obtained from the rings but higher than the values measured on the floor. This suggests that the training aids are easier to control than the rings. The rails 2, 3 and 4 trials, produced the highest EMG values of all of the training aids.

Medial Deltoid: Again, all of the training aids produced lower values than from the rings, but higher than the floor values. The rails 2 trial and rails 3 trial produced the highest reading of the training aids, except for the rails 5 trial which was 492% of the rings value.

Posterior Deltoid: The rocker produced much lower EMG values than both floor and rings, it achieved only 12% of the value of rings. The bowls produced readings very similar to the rings. The rails 1, 2 and 3 trials produced values higher than were measured on the rings, but the same as was measured on the floor. The rails 4 trial was lower than the floor and the rings. This was assumed to be as the skill was in perfect balance, hence the shoulders were not required to be fully engaged (87% of the rings value). The fifth rail trial created very low EMG readings.

Extensor Carpi Radialis Longus: The rocker achieved a value 24% of rings value. However it was evident during the trial that the wrists needed to be loose in order to permit balancing movements on the training aid. Similarly the bowls achieved only 18% of rings value measured. The rails 1 trial was measured to have 39% of value measured on the rings, with rails 2 = 50% of the rings; rails 3 = 33% of rings; rails 4 = 24% of the rings; and rails 5 = 663% of the rings, (as the skill was a struggle to hold).

Flexor Carpi Radialis: The rocker produced an EMG value that was much lower than the values measured on both the floor and the rings. The bowl followed the same trend. During rail trials 1 and 2, the EMG value measured was much higher than the value measured on the rings, (157% and 158% respectively of rings). The

rails 3 trial was measured to have a value 89% of rings value, and the rails 4 trial was measured to have 78% of rings value. The rails 5 trial, during which the gymnast lost his balance, produced an EMG value which was 582% of the value measured during the rings performance.

Flexor Carpi Ulnaris: The rocker was measured to have a much lower EMG value than either the floor or the rings, suggesting no wrist flexion occurred on this training aid. The bowls also produced a value much lower than the rings, but slightly higher than the floor value, suggesting wrist flexion was present. The rails 1 and 2 trials produced values higher than the rings, (111% and 116% respectively of rings), with the rails 3 trial equalling only 37% of rings, and the rails 4 trial equalling 33% of rings, in agreement with the familiarisation assumption. The rails 5 trial produced an EMG value of only 39% of rings.

Triceps Brachii: As with the wrist flexors and extensors, the rocker, and bowls produced much lower EMG values for the Triceps Brachii than were measured for the floor and the rings. The rails 1 and 2 trials produced the highest values of all of the training aids, but these values were still only 30% and 44% respectively of rings value. The rails 3 trial was measured to have 27% of the rings value, and the rails 4 trial was measured to have only 6% of the rings value. This was expected as the handstand was so stationary. The Triceps Brachii were not needed to stabilise arms during the rails 4 trial. However during the rails 5 trial during the loss of balance, the EMG value was measured to be 85% of the value measured on the rings.

EMG Trace

The shape of the trace produced from the EMG signal was also of importance, as this provided information about what the muscles were doing, i.e. turning on and off or if they only experienced tremor. As discussed previously in the chapter (Section 6.4.2), sharp steeply rising signals, which were much higher than the base average amplitude of the trace (Figure 6.10) are indicative of muscles which are controlling or stabilising a movement (co-contraction). Flat traces with slight fluctuation or 'wobble' are more generally related to muscle tremor, or if of a low signal magnitude, then relatively no muscle activation is occurring. The EMG traces collected during the performances were analysed, and the shape of the trace produced by each muscle has been categorised in Table 6.11 below.

- Key:**
- 5 – Jagged, lots of peaks
 - 4 – Continuously very spiky
 - 3 - Spiky with a few peaks
 - 2 - Wiggly with a few spikes
 - 1 - Smooth wiggle

Table 6-11: EMG Graph information for each trial

	RF	GM	RA	AD	MD	PD	ECRL	FCR	FCU	TB
Floor	3	5	3	5	5	5	2	3	5	5
Rings	2	2	2	3	3	4	2	3	2	2
Rocker	3	2	2	4	4	3	3	5	5	3
Bowls	1	2	2	3	3	3	3	1	1	1
Rails 1	2	2	2	3	3	3	3	1	2	1
Rails 2	2	2	2	3	2	2	2	1	2	1
Rails 3	2	3	2	2	2	2	2	2	4	2
Rails 4	2	2	1	2	3	2	2	2	2	2
Rails 5	2	1	2	2	2	3	2	3	2	2

6.6.3 Force data

As mentioned previously each of the training aids were placed on a rigid wooden surface which was securely attached to the force platform. Gymnastics matting carpet was also placed and secured on top of the wooden surface to ensure that the training aids were analysed on the same surface as they would have when in use in a gymnasium.

6.6.4 Training aid comparison - force results

Peak horizontal forces in the x and y directions were obtained from the force plate for each training aid. The force plate was zeroed with the individual training aids in place before data was collected (Table 6.12).

Table 6-12: Peak force data for all trials (F_x – is forward and back, F_y – is sideways)

Peak horizontal forces	F_x (N)	F_y (N)
Floor Handstand	32.0	19.8
Rings Handstand	77.5	31.4
Rocker	87.5	27.8
Bowls	129.5	37.9
Rails 1	43.0	30.9
Rails 2	43.0	35.4
Rails 3	43.8	23.5
Rails 4	37.0	17.7
Rails 5	57.6	23.1

Rocker

The value of F_y (sideways force) was fairly low, which is expected as the training aid rocks forwards and backward. There should therefore be very little force sideways as the training aid is unable to move in this direction. Back and forth (F_x), the force is larger due to the movement of the mass centre (as can be seen from the motion analysis which is discussed in Section 6.6.5). This is due to the fact that the gymnast must be pushing the training aid forwards and backwards to correct the balance, moving his mass centre in the process.

The forward and backward corrective action is possible as there is sufficient friction present between the rocker (which has a rubber bottom) and the ground. The gymnast is therefore capable of pushing through the training aid directly against the floor and using a corrective wrist torque to restore his balance in the handstand (Figure 6.22). This is not at all possible on the rings as there is no friction within the system. This training aid required the gymnast to move his base of support in order to maintain balance as on the rings, and so more movement of the centre of pressure (COP) would be measured than would be observed on the floor. However the training aid also used the wrists to help control the balance, the same way as the floor balance does. On the rings the wrists should not flex, as there is nothing to push against with a wrist torque.

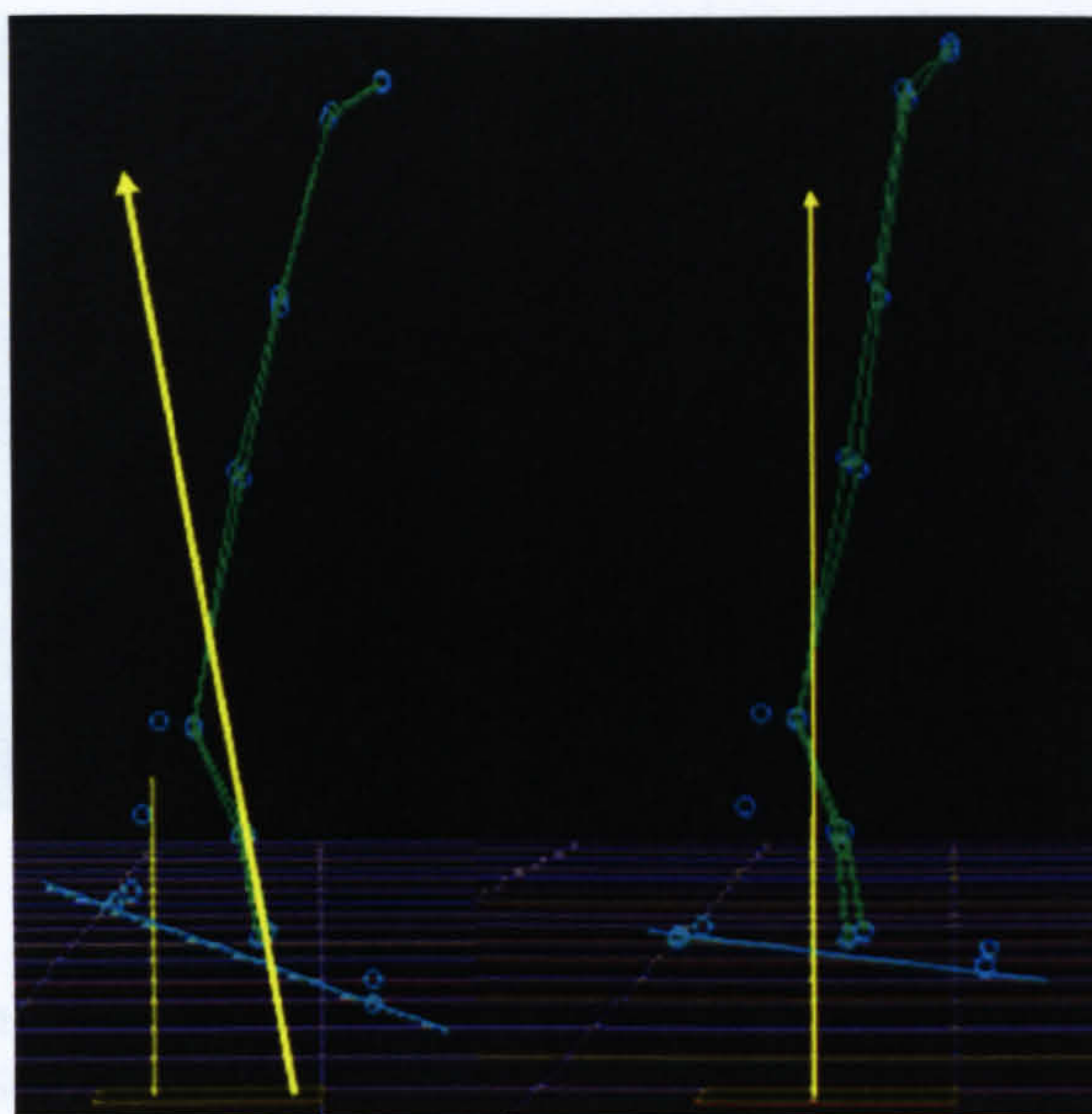


Figure 6-22: Handstand on the rocker, COP movement: (a) mass centre moving forwards, wrists flexed (b) mass centre stationary.

Handstand Rails

Therefore on the handstand rocker training aid a different technique is being used than on both the floor and the rings. More evidence of this will be discussed later in the chapter when joint movement is discussed.

Bowls

The handstand bowls had one of the highest peak horizontal component forces in the whole data collection, and this was due to the nature of the training aid. As the bowls work on a similar principal to the rocker, but can rock in all directions (not just back and forth), the incorrect technique possible on this training aid is greater than on the rocker. This is shown by the force magnitudes produced.

Figure 6.23 shows a variety of 'snapshots' of gymnast R performing a handstand on the bowls. The figure illustrates the body configuration of the gymnast with respect to the orientation of the training aid beneath him. During the performance on the bowls, as can be seen in Figure 6.23(b) below, the gymnast is in a position which is physically impossible without flexion and adduction of the wrists. This is again a technique very dissimilar to the technique used on the rings as no wrist action is used to control the handstand balance on the rings, only tension in the wrists is present, to stabilise the joint and prevent any joint movement. The training aid does however, like the rocker, require the gymnast to move his base of support, hence creating more movement of the COP during this skill than would be observed on the floor. The distortion of the elbow joint in Figure 6.23(b) is due to marker positions being on the inside of the elbow and the front of the wrist.

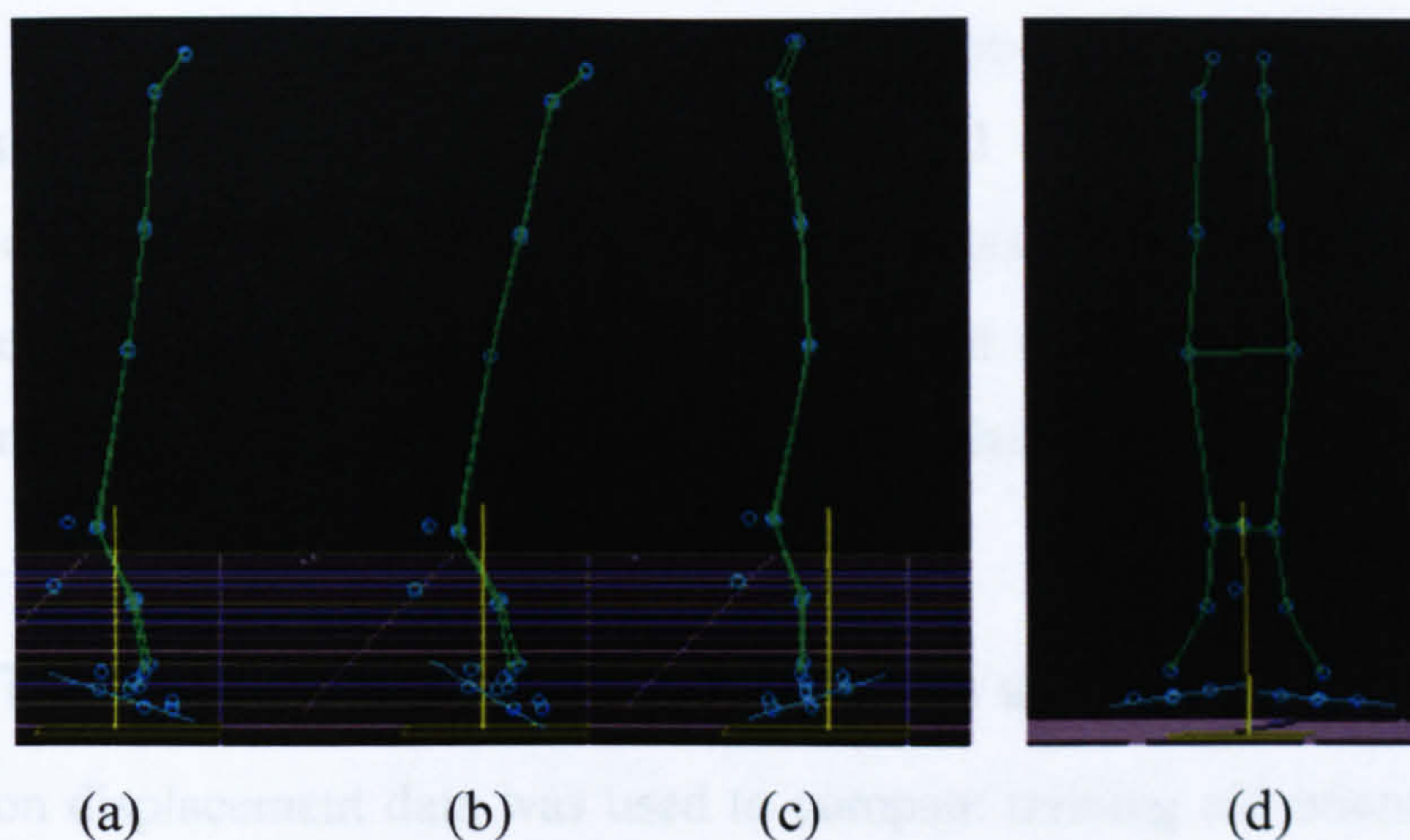


Figure 6-23: Handstand Bowls corrective actions: (a) average position of the training aid with a good handstand shape; (b) body configuration during maximum forward tilt of the training aid; (c) body configuration during maximum backward tilt of the training aid; (d) front view of average handstand position on the bowls.

Handstand Rails

The set of results from the rails training aid which best replicated the data collected from rings trial was produced during the rails 4 trial. This was to be expected as it was the most similar to the rings of all of the possible training aid configurations, since it permitted movement in all directions.

Almost all of the forces measured during trials on the rails handstand training aid were lower than both the handstand bowls and the handstand rocker in both the x and y direction. The only exception to this was during the rails 1 and 2 trials when the forces measured sideways were slightly higher than on the rocker. This was not surprising as for these two performances, the wrists were restricted from moving sideways, and therefore, the wrists were capable of producing a force sideways into the static handle. They were however lower than the forces produced when using the bowls.

All the forces measured for the rails training aid were lower than for the rings, which suggests that less movement had taken place, and therefore the training aid was slightly easier than the real rings. There is no way for the rails to permit a corrective wrist torque as they are on a very low friction surface on the flat, the handles slide away if the subject attempts to push.

6.6.5 Motion analysis data

During the testing of the training aids, as mentioned previously, markers were located on the corners of the training aids to enable an analysis of the position of the

training aid relative to the floor during the performances. In the following section the data collected from these markers will be discussed with regards to the observed movement each of the training aids during use. This information will be used to compare the environment experienced by the gymnast whilst on each training aid, to the environment experienced whilst performing a handstand on the rings.

6.6.6 Training aid comparison – motion analysis results

Vicon displacement data was used to compare training aid orientations. This data was then corrected with the measured anthropometric marker-offset values and post-processed to obtain joint centre movement, mass centre movement and body orientation.

Vicon

To help visualise the body configuration whilst on the training aid, images of the marker positions during the performances have been captured from the Vicon workstation (Figure 6.24). As can be seen from Figure 6.24, the three training aids act differently, orientating the gymnast in different positions during the performance of the handstand balance. Whilst performing a handstand on the training aids, the gymnast should ‘feel’ and ‘look’ like he is performing the skill on the rings. Figure 6.24 below, shows that both the bowls and the rocker *tip* the gymnast to an angle which is impossible to achieve during a handstand on the rings. To create such an angle of tilt of the training aid requires abduction of the wrist, which is not possible on the rings.

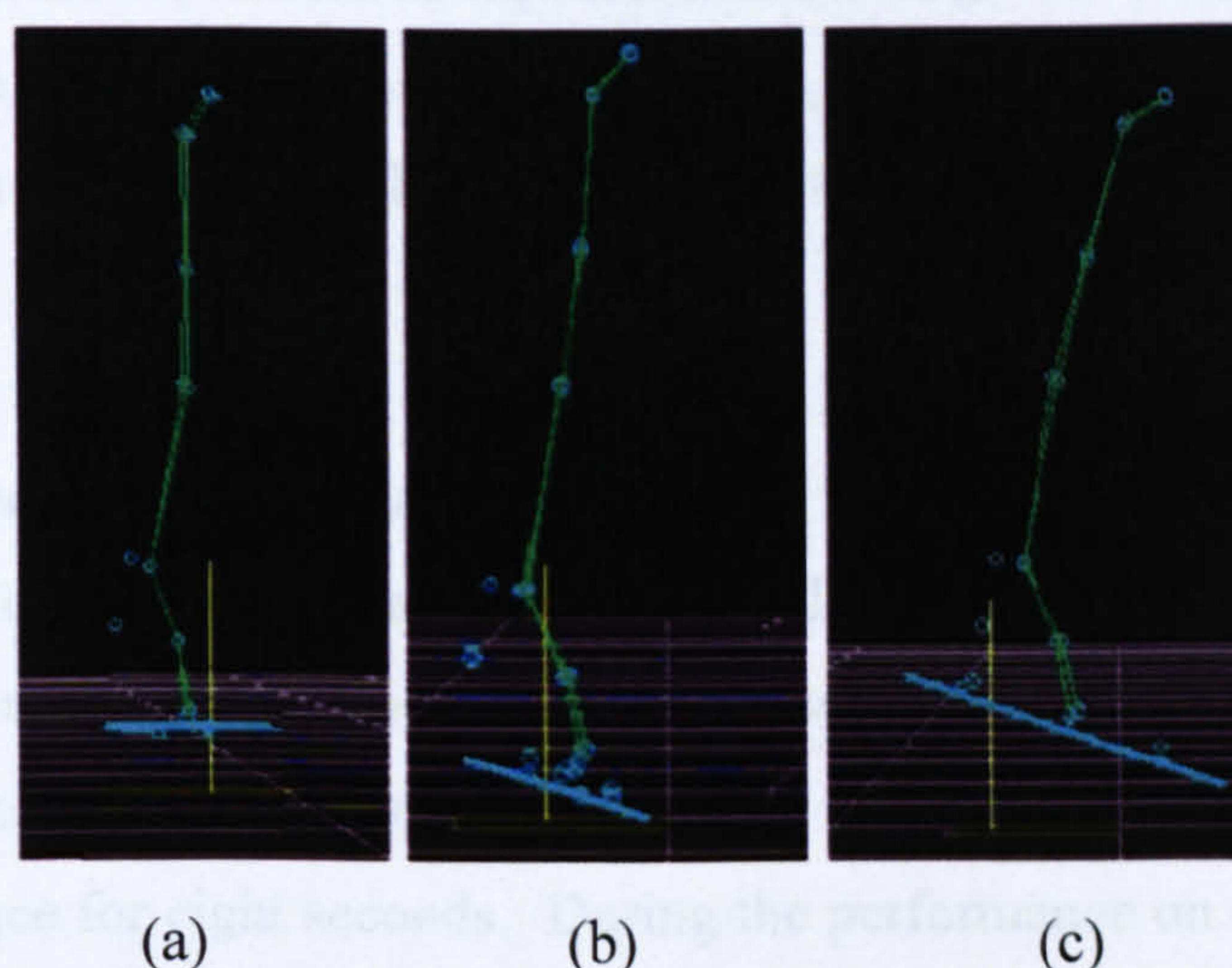


Figure 6-24: A comparison of gymnast R's average body configurations for the best handstand position held during the trials on the three different training aids: (a) handstand on the rails; (b) handstand on the bowls; (c) handstand on the rocker.

From the data it can be measured that the front and back of the rocker, travelled up and down a distance of 97mm in the z direction. The front two markers move back and forth (x) by a displacement of 109mm, the back markers move only a distance of 66mm forward as the weight was not directly through the centre of the training aid. The training aid travelled only 4mm sideways (y).

When using the bowls, the left and right hands move independently which was more like on the rings. The movement measured for the left bowl was 88mm up and down in z, while the right moved 102mm. The left bowl moved 59mm back and forth, and the right moved 69mm. The left bowl moved 49mm sideways and the right bowl moved 57mm.

The rails 4 trial was the configuration designed to represent the actual rings, during this trial the left and right handle both were measured to move only 3mm up and down, which is essentially no movement as was expected as the rails were not capable of moving up and down, and hence this 3mm was probably produced by marker movement. This will have been due to marker movement as the handles could not move up and down. The left handle travelled 68mm back and forth, and the right handle travelled 48mm. The two handles travelled by different distances as there was a slight twist in the handstand during the performance. Although hands may move back and forth by slightly different amounts whilst performing a handstand on the rings, twist cannot happen due to the restoring forces of the cables. The problem of the gymnast twisting while in handstand on the prototype training aid may need to be addressed if it is considered to be a problem. Sideways, the left handle travelled by 71mm, and the right handle travelled 57mm.

The maximum movement of each hand on the rings was measured to be 91mm sideways, 172mm back and forth when there was presence of slight swing. With a suspension length of 3 metres, this corresponds to a movement of 0.5mm up and down.

Joint Centre Movement and Joint Angles

The joint centre movement was calculated and then graphed (Appendix E). The handstands were all held for a duration of ten seconds, except for the performance on the bowls and the second rails trial, when the gymnast only succeeded in maintaining balance for eight seconds. During the performance on the rocker and the bowls, the joint centres which had the greatest displacement were the toe markers. This is because when the gymnast was moving back and forth by a significant amount,

the hip angle was also changing, and this increased the range of movement at the feet. With all of the trials on the rails it seemed that it was again the toes which had the greatest displacement of the measured joint centres. This was due to the amount of movement present during the trials, and again because of the amount of variation measured at the hip angle.

Rocker: The wrists had a movement range of 122mm, the toes had a movement range of 238mm, and the shoulders had a movement range of 36mm back and forth. Figure 6.220(c) shows that the feet were in fact so far behind the wrists that the subject had a very closed shoulder angle, and abduction of the wrist, which was never observed during the rings trial. The shoulders were moving less than the wrists during this balance which suggests that the gymnast was employing the rings control strategy. However due to the body configuration, and the presence of significant wrist control, the data suggests that the gymnast was not using the same balance control technique of shoulder angle movement with 'locked' wrists, as was observed during the handstand on the rings.

Bowls: The subject struggled to hold this handstand on this training aid, therefore although other trials were held for ten seconds, this trial was held for only eight seconds. The wrists had a movement range of 126mm, and the toes had a movement range of 1132mm. The toes moved a distance of over a metre which is very considerable. The shoulder had a movement range of 32mm, and although the wrists had again moved more than the shoulder, the flexion observed at the wrist suggested that the performance on the training aid did not use the control strategy observed during the performance on the rings.

Rails 1: This balance was almost stationary with some slight movement from the toes. The toes had a movement range of 111mm, the wrists had a movement range of 0.4mm, and the shoulders had a movement range of 13mm. No balance control could be accurately detected due to movements of less than 20mm at the shoulders and wrists, but elements of both the floor and rings control strategies were present.

Rails 2: As more degrees of freedom were introduced, more movement was observed during the balance. The movement range for the toes increased to 147mm, the wrists had a movement range of 6mm, and the shoulder has a movement range of 40mm. With still only 40mm of movement of the shoulders, and less at the wrists, still no control strategy could be clearly identified, and elements of both the floor (moving the mass centre over the stationary base of support) and rings control strategies (moving the base of support under the centre of mass using movement of the

shoulder angle) were present. It is possible that with only back and forth movement released on the training aid, there was sufficient friction for the gymnast to use the floor technique to control only small movements. However, as $F \leq \mu_s R$, and $F = ma$, as wrist acceleration increases as movements become more jerky, once $a > \mu_k R$, (where μ_s = static coefficient of friction and μ_k = kinetic coefficient of friction) the frictional forces would be overcome and the wrists would move.

Rails 3: During this trial the toes movement range was 293mm, the wrist movement range was 71mm, and the shoulder movement range was 40mm. With the training aid at this setting, it became evident that the gymnast was now required to employ a similar control strategy (moving the base of support under the mass centre using movement of the shoulder angle) to that observed during the rings handstand. As the wrists were moving more than the shoulders, the gymnast appeared to be moving his base of support under his mass centre to maintain balance.

Rails 4: This balance was again almost stationary like the first rails trial. The toes movement range was 142mm, the wrist movement range was 32mm, and the shoulders movement range was only 30mm. Although there was only a slight difference in the movement of the wrists and of the shoulders, during the trial, the gymnast was observed to be still using a similar shoulder angle control strategy to the previous trial.

Rails 5: This trial was introduced to simulate a novice gymnast using the training aid. More significant movement was therefore observed. The toes movement range was 247mm, the wrist movement range was 27mm, and the shoulder movement range was 21mm. Even when losing control, the gymnast still appeared to employ the shoulder angle control strategy observed on the rings, as he moved his hands back under his mass centre in an attempt to maintain balance.

Table 6.13 below contains details of the hip and shoulder angle for each of the nine trials.

Table 6-13: Comparison of angles for all handstand trials ($\pm 0.4^\circ$)

		Maximum angle	Minimum angle	Range	Average angle	Angle range ratio
Floor	Shoulder ($^\circ$)	149	145	6	145	2.10
	Hip ($^\circ$)	179	177	2	178	
Rings	Shoulder ($^\circ$)	154	141	13	147	0.60
	Hip ($^\circ$)	178	157	21	167	
Rocker	Shoulder ($^\circ$)	147	140	7	143	0.91
	Hip ($^\circ$)	180	172	8	176	

Bowls	Shoulder (°)	147	139	8	143	0.29
	Hip (°)	178	152	26	165	
Rails 1	Shoulder (°)	149	140	9	144	0.59
	Hip (°)	174	159	15	167	
Rails 2	Shoulder (°)	147	140	7	144	0.281
	Hip (°)	178	153	25	165	
Rails 3	Shoulder (°)	153	139	14	146	0.65
	Hip (°)	177	156	21	166	
Rails 4	Shoulder (°)	147	139	8	143	0.68
	Hip (°)	174	162	12	168	
Rails 5	Shoulder (°)	143	135	8	139	0.47
	Hip (°)	172	155	17	163	

When comparing these two angles it was possible to assess which joint was controlling the majority of the balance. Although generally no considerable movement should be seen at the hip angle during a good handstand on the rings, as was discussed earlier in Section 6.6.2, gymnast R seemed to have a tendency to utilise hip control during the rings handstand. If a training aid truly resembles the rings, then the same method of balance control should be observed.

Rocker: During this trial the hip angle was measured to have a higher average position than when the balance was performed on the rings, meaning that the body was in a straighter configuration with more open hips. The measured shoulder angle had a lower range and lower average angle than was measured on the rings. Comparing these angles, it was shown that gymnast R was using nearly equal amounts of hip and shoulder to control the balance. The ratio of 0.91, shows that the gymnast used a larger proportion of shoulder control during this balance than he did during the rings balance which had a ratio of only 0.60.

Bowls: During the performance on the handstand bowls, the hip angle measured was more closed than when performed on the rings, giving the gymnast a more dished body shape. Much more movement at hips was recorded, suggesting less control was present during this balance. The shoulder angle was measured to be smaller than on the rings, and less movement was detected. The control of this balance was mainly through the hip angle with an angle range ration of 0.29, unlike the rings which had a ratio of 0.60 due to the larger proportion of shoulder control.

Rails 1: The hips were measured to have less movement during this trial than when on the rings. Rails trial 1 had very similar average angles to the rings, but better control as there was less movement during the performance. There was also less

movement at the shoulder, although the average angle was smaller. This may be due to the balance on the training aid being easier to control. The angle range ratio was calculated to have almost identical proportions of shoulder and hip control, to the rings, suggesting the gymnast used of a very similar control technique to which he used on the rings.

Rails 2: During this trial the hips moved by a similar amount to when the handstand was performed on the rings, but had a smaller average angle. The shoulders were measured to have less movement with a smaller average angle than when on the rings. This trial, like the bowls trial used too higher a proportion of hip control to resemble the control used on the rings.

Rails 3: During the third rails trial, the hip produced a very similar range of movement as was seen during the performance on the rings. A very similar average angle was also measured for the hips. The shoulders had a very similar angle range to the rings performance, but were slightly more closed. Gymnast R used his shoulders a little more during the control of this balance than when on the rings, but overall utilised very similar shoulder angle control to what was observed during the rings trial.

Rail 4: The hip was measured to produce less movement than on the rings, but with a very similar average angle. The shoulders had a smaller range of movement and a slightly smaller angle than the rings. This performance used the shoulders even more than the third rails trial during the control. During this trial, a better technique than was observed to be used on rings was used to control this balance. However, as the handstand was very still during this performance, it would have been easier to use good technique. It has been observed that when less control is present in the balance, gymnast R used his hips more, and this may be due to a lack of body tension control.

Rails 5: Although during this performance there was a loss of control, there was still less movement and a smaller average angle measured at the hip than was observed during the performance on the rings. The shoulder also had a smaller range and a smaller angle than the rings trial. However when considering the average angle ratio of the two joint angles, gymnast R again used more hip control than shoulder control making the ratio (0.47) lower than on the rings (0.60).

Shoulder Angle

The shoulder angle range should be the biggest during the performance on the rings due to the skill being balanced by moving the wrists back and forth under the

mass centre. All of the training aids had less shoulder angle movement than rings except the third rail trial. This will be partly due to the other performances being more stable balances, except for the bowls trial. However if the average angle was too low for example during the rocker, bowls and second rail trial, then it must be assumed that a different form of balance control than utilised on the rings was taking place.

Hip Angle

A lot of movement was observed at the hip during the performance on the rings, and very little was observed during the performance on the floor. It is assumed that this may be due to the capabilities of body control possessed by gymnast R, but it also may be a difference in the way the gymnast controls the two balances.

The balance on the floor should have minimum hip movement as this balance primarily uses wrist control. The rocker had much lower hip joint movement than the rings, suggesting that the balance was too easy; the bowls had substantially higher movement, indicating that the subject found it harder to balance; the rails had slightly lower movement, but with a similar enough value to indicate that gymnast R found the rails training aid just a little easier to balance on than the rings.

Mass Centre Movement and Mass Centre – Wrist Relationship

As for the handstand on floor and rings, the position of the mass centre, wrist and the difference between the position of the mass centre and wrist will now be investigated. The results of this analysis are compiled below in Table 6.14.

**Table 6-14: Comparison of all positional data for all handstand trials
(displacement ± 1 mm, angle $\pm 0.4^\circ$)**

Floor	Max position	Min position	Range (m)	Average position
Mass centre x	0.29	0.27	0.02	0.28
Mass centre y	0.21	0.20	0.01	0.21
Wrist x	0.21	0.21	0.01	0.21
Wrist y	0.21	0.20	0.00	0.20
Mass centre – wrist (x)	0.08	0.06	0.02	0.07
Mass centre – wrist (y)	0.01	0.00	0.01	0.00
Somersault angle ($^\circ$)	5	4	1	4
Tilt ($^\circ$)	1	0	1	0
Rings	Max position	Min position	Range (m)	Average position
Mass centre x	0.39	0.21	0.18	0.30
Mass centre y	0.26	0.21	0.05	0.24
Wrist x	0.39	0.13	0.26	0.26
Wrist y	0.24	0.19	0.05	0.21
Mass centre – wrist (x)	0.10	0.00	0.10	0.05

Mass centre – wrist (y)	0.03	0.01	0.02	0.02
Somersault angle (°)	6	-1	7	3
Tilt (°)	2	1	1	1
Rocker	Max position	Min position	Range (m)	Average position
Mass centre x	0.28	0.21	0.07	0.24
Mass centre y	0.23	0.18	0.05	0.21
Wrist x	0.24	0.15	0.10	0.20
Wrist y	0.22	0.21	0.01	0.21
Mass centre – wrist (x)	0.08	0.01	0.07	0.04
Mass centre – wrist (y)	0.03	0.00	0.03	0.01
Somersault angle (°)	5	1	4	3
Tilt (°)	1	-2	3	0
Bowls	Max position	Min position	Range (m)	Average position
Mass centre x	0.37	0.31	0.06	0.34
Mass centre y	0.23	0.19	0.04	0.21
Wrist x	0.37	0.24	0.13	0.30
Wrist y	0.21	0.20	0.01	0.21
Mass centre – wrist (x)	0.07	0.00	0.07	0.04
Mass centre – wrist (y)	0.02	0.00	0.02	0.01
Somersault angle (°)	4	0	5	2
Tilt (°)	1	-1	2	0
Rails 1	Max position	Min position	Range (m)	Average position
Mass centre x	0.42	0.38	0.04	0.40
Mass centre y	0.23	0.21	0.02	0.22
Wrist x	0.39	0.36	0.04	0.38
Wrist y	0.20	0.20	0.00	0.20
Mass centre – wrist (x)	0.04	0.02	0.02	0.03
Mass centre – wrist (y)	0.03	0.01	0.02	0.02
Somersault angle (°)	2	1	1	2
Tilt (°)	2	1	1	1
Rails 2	Max position	Min position	Range (m)	Average position
Mass centre x	0.41	0.30	0.12	0.36
Mass centre y	0.27	0.23	0.04	0.25
Wrist x	0.37	0.26	0.11	0.31
Wrist y	0.21	0.20	0.01	0.21
Mass centre – wrist (x)	0.08	0.03	0.05	0.05
Mass centre – wrist (y)	0.06	0.03	0.04	0.05
Somersault angle (°)	5	2	3	3
Tilt (°)	4	2	2	3
Rails 3	Max position	Min position	Range (m)	Average position
Mass centre x	0.29	0.24	0.06	0.27
Mass centre y	0.22	0.18	0.04	0.20
Wrist x	0.27	0.20	0.07	0.23
Wrist y	0.20	0.16	0.04	0.18
Mass centre – wrist (x)	0.06	0.01	0.05	0.04
Mass centre – wrist (y)	0.02	0.00	0.02	0.01
Somersault angle (°)	4	1	3	2
Tilt (°)	1	0	2	1
Rails 4	Max position	Min position	Range (m)	Average position
Mass centre x	0.40	0.36	0.04	0.38
Mass centre y	0.24	0.20	0.05	0.22
Wrist x	0.38	0.34	0.04	0.36
Wrist y	0.23	0.20	0.03	0.21
Mass centre – wrist (x)	0.04	0.01	0.03	0.03

Mass centre – wrist (y)	0.03	0.00	0.03	0.01
Somersault angle (°)	3	1	2	2
Tilt (°)	2	0	2	1
Rails 5	Max position	Min position	Range (m)	Average position
Mass centre x	0.35	0.30	0.05	0.33
Mass centre y	0.18	0.16	0.01	0.17
Wrist x	0.34	0.30	0.04	0.32
Wrist y	0.18	0.16	0.02	0.17
Mass centre – wrist (x)	0.04	0.00	0.04	0.02
Mass centre – wrist (y)	0.01	0.00	0.01	0.01
Somersault angle (°)	3	0	3	1
Tilt (°)	1	-1	1	0

The value of the difference between the mass centre position and the wrists back and forth (x) is an indication of how good the handstand is. If this value is small then the handstand is still and in a good configuration. Larger values suggest more movement during the balance, or a poor body configuration. In all of the trials except the handstand on the floor, it is expected that the movement of the mass centre back and forth should be zero. As discussed previously this was not the case for the rings handstand due to there being some swing present during the trial. The results presented in Table 6.14 are discussed below:

Rocker: The mass centre was measured to have a small amount of movement back and forth during the balance. However, the wrists did move slightly more than the mass centre, which suggests a similar technique to the rings was being used to control the balance, but that the gymnast was still capable of moving his mass centre during the performance as in the floor balance to help him maintain balance. The mass centre during this trial in fact moved more than three times the amount observed during the handstand trial.

The mass centre to wrist distance back and forth on the rocker was slightly higher than the values measured on the rings and on the floor, which suggested that the performance on this training aid was more difficult than on the rings, and there was a smaller range in the somersault angle (Figure 6.16) suggesting that the gymnast used a straighter more vertical body configuration during this performance. There was also a greater tilt angle suggesting that the hands were not quite parallel or that the gymnast may have been favouring one shoulder.

Bowls: The mass centre again moved during this trial approximately three times the amount measured during the floor trial. The wrists did however move more than the mass centre, suggesting that a similar technique was used to control the balance as was observed during the performance on the rocker. The mass centre to

wrist distance was very similar to that observed on the rings, but the somersault angle was less than on the rings, which suggests that although the balance on this training aid was of a similar difficulty to the handstand on the rings, it was achieved using a different body configuration. The tilt angle was similar to the rocker.

Rails 1: During this trial the mass centre and wrists moved by very similar amounts, and with a mass centre to wrist distance of only 18mm, this performance appeared to be a fairly stationary handstand. With only one degree of freedom released for this set up (both arms moving back and forth together), this performance appeared to use both the techniques observed on the floor and on the rings; it had a similar somersault angle to the floor performance, but it was easier to maintain the balance than it was on the rings. This would be a good first progression for a novice gymnast.

Rails 2: This trial gave very similar results to the rails 1 performance. The main difference was the magnitude of movement of the mass centre and the wrists, which although very similar to each other were closer in size to those measured on the rings. The somersault angle was slightly larger than during the rails 1 performance, but still closer to the value measured on the floor than was measured on the rings. With two degrees of freedom (the arms moving back and forth independently) now released, the performance on the training aid became more similar to the performance observed on the rings.

Rails 3: During this trial, the wrists moved more than the mass centre did, as was observed during the trial on the rings. The mass centre to wrist distance was almost identical to the value measured during the rings performance, but the somersault angle range was still only half of the value measured during the rings trial. This suggested that a very similar balance was performed on both the rings and the training aid with four degrees of freedom released (each arm free to move backward, forwards and sideways), but that the training aid balance was easier than the rings balance and so maintained a higher level of control.

Rails 4: As the balance was very stable none of the measurements taken were similar to those measured during the performance on the rings.

Rails 5: Even though the control of the balance was lost during the performance, the mass centre and the wrists did not move as far back and forth as on the rings, as it was the hip angle which did the majority of the balance control rather than the shoulders. The mass centre moved slightly more than the wrists, and this may have been because the training aid was not completely frictionless. Both the

mass centre to wrist distance and the somersault angle were smaller than on the rings, and the tilt angle was very similar to that measured on the rings.

6.6.7 Summary of Comparison

Rocker

This training aid generally did not simulate the same muscular activation as was observed during the rings trial. The most important difference was the activation of the wrist flexors and extensors which highlighted the fact that this training aid was recruiting the wrist to control the balance, rather than utilising the muscles to stabilise the joint. The forces measured were also in agreement with this. The rocker prevented any lateral movement of the wrists sideways, and body configurations observed during this trial were not observed during the performance on the rings. The data however, does show that the wrists moved more than the mass centre during the balance, which is the same as observed during the trial on the rings. Overall the performance on this training aid was observed to have some of the same elements of the floor control (the mass centre moves over the base of support using a wrist torque), and some of the same elements as the rings (using movement of the shoulder angle to move the wrists under the mass centre).

Bowls

As with the handstand rocker, the performance on this training aid did not show the same muscle activation trends as were observed during the performance on the rings. The exception to this was the value obtained from the Posterior Deltoid, which suggested that some shoulder control took place. This was in agreement with the wrists being measured to have moved more than the mass centre. However, with the wrist activation present in the same manner as was observed during the rocker trial, it was again observed that this training aid utilised the wrists to control the balance as well as the shoulder angle. As the bowls were so small, although the wrists could move in the same direction as on the rings, they were incapable of moving the same distance as was observed on the rings. The gymnast struggled to maintain balance on this training aid, but he performed a stable handstand on the rings, this suggests that the same control was not required to maintain balance. He also maintained a different body configuration during the balance on the bowls, which

again suggests that this training aid used the same type of control as was observed during the handstand on the rocker.

Rails

In general the rails recruited a more similar muscle activation pattern to the rings than any of the other training aids. Although the muscles which controlled the gymnast's body tension were measured to be activated at a higher level, the rails trials had the most similar shoulder activations of all of the training aids, and had wrist activation which suggested intense joint stability through co-contraction. Forces were found to be the most similar to rings when the training aid had all the degrees of freedom released, and so long as a minimum of the first four degrees of freedom were released (each arm free to move backward, forwards and sideways), this training aid recruited the same type of shoulder control to maintain balance as was observed on the rings. During the lower settings of the training aid, the body configurations of the gymnast were close to those observed on the rings, and overall the similarity between the handstand on the training aid and the rings improved as more degrees of freedom were released. This is the advantage of a multi-stage training aid, as it permits the gymnast to learn the skill in stages and progress to a more complex environment as the gymnast's ability and strength increases.

This training aid was designed to permit a range of ability and sizes of gymnast to learn a handstand on the rings. From the muscle, the force, and the movement data analysed within this chapter it is evident that this has been accomplished, and that this training aid has exceeded the abilities of both of the existing training aids by being the only training aid to actually incorporate the same control strategy which was observed during the handstand on the rings.

6.6.8 Coach and gymnast feedback

Separate to the data collection, six different elite male Artistic gymnasts performed handstands on the prototype rails training aid. Informal discussions were also held in order to gain feedback on the training aid. These discussions, alongside the interviews with the coaches and gymnasts involved in the investigation, provided some very positive and very useful feedback. One of the most useful comments was that the wrist rotation movement should be the second degree of freedom to be released after the backward-forward motion with synchronised wrists, and that the

sideways motion should be the last. This was to enable the handstand control to be the same as on the rings, as the gymnast would need to be moving the wrists in a curved path through a pronation - supination motion of the arms.

The training aid was commended by an International High Performance Coach, Mr G. Predescu, for being the only training aid that gave the gymnast a psychological feeling of movement as experienced on the rings, and that once the wrists were released, the training aid felt very similar to the rings but minus the restoring forces. Comments were made to suggest that if restoring forces could also be added to the training aid it would almost completely mimic the rings.

The final comments were that the rings trainer prototype was an excellent training aid. It simplified the learning process, basic settings were considerably easier than the rings, and the final setting was only slightly easier to use than the rings meaning that the training aid had met customer requirements. When demonstrated to John Atkinson (F.I.G Technical Committee), his comment was: 'so simple yet so brilliant, this will be a very useful piece of training equipment for gymnasts'.

6.7 Chapter summary

This chapter has described two separate data collections, and has then discussed the variety of results obtained from each, including kinematics, EMG and force data. The prototype and existing training aids have been assessed by comparison against both the floor handstand, the rings handstand and against each other, and the outcomes have been discussed (Section 6.6.7). The prototype rails training aid was capable of permitting a 'rings handstand' to be performed on it by several elite male gymnasts, and it has been shown that it does not encourage wrist control, unlike existing training aids.

The Vicon data collected showed that the rocker had movement of 97mm up and down and 109mm back and forth; the bowls had movement of 102mm up and down, 69mm back and forth, and 57mm side to side; the rails (when all degrees of freedom were released) showed 3mm of movement up and down, 68mm of travel back and forth, and 71mm of travel side to side. Finally the rings were measured to have 0.5mm of travel up and down, 172mm of travel back and forth including swing, and 91mm of travel side to side (Section 6.6.6). From this it was determined that the data collected from the rails most closely replicated the data measured on the rings

due to the magnitude of sideways travel, and movement up and down and the fact that none of the aids incorporated swing.

From the EMG data, for the majority of muscles measured the rails training aid produced the largest signal, however the shape of the EMG traces produced from the muscles in the wrist showed that only muscle tremor occurred on the training aid when fully simulating the rings, whereas on the rocker and bowls training aids active muscle control was observed (Figure 6.20, Table 6.10 and Table 6.11). The force data collected showed that the highest horizontal forces were present on the bowls (130N back and forth and 38N sideways), and that the floor had the lowest values (32N back and forth and 20N sideways); however, the rails training aid with all degrees of freedom released had the second lowest forces measured (Table 6.12) due to its low friction properties.

There has been very positive feedback from both coaches and gymnasts involved in the investigation, and the general overview of the results obtained has been that the prototype training aid has generally out-performed the existing training aids, especially when most of the movement degrees of freedom were released.

Suggestions have been provided for possible modifications to the training aid, but all participants involved in the study were more than content with the training aid as was initially designed. Any modifications suggested were only as a matter of interest rather than necessity, for example: expanding the use of the training aid for conditioning purposes as well. The next section of this thesis will focus on the backward handspring training aid.

7

Backward Handspring Analysis

7.1 Mechanical analysis of the backward handspring

In order to analyse a dynamic skill such as a backward handspring, it is necessary to first establish the biomechanical requirements of the movement. This will permit an accurate comparison between performances and between different techniques.

7.1.1 Introduction

It is important to understand the variation in possible techniques used to perform a chosen skill when designing a training aid. This is to ensure that the equipment has been developed with insight into the possible techniques which a gymnast may employ when using the training aid.

In the literature reviewed in Chapter 3, various studies have researched the biomechanical process of performing a backward handspring, but none have actually described the entire skill in terms of equations of motion. To facilitate this analysis, it has been decided to analyse the backward handspring as a 2-D planar motion. This is an acceptable assumption as the movement should be symmetrical about the sagittal plane in a good performance.

The skill will be broken down into constituent components to enable each stage of the backward handspring to be described in biomechanical terms. The energy will be assumed to be conserved between these stages unless otherwise stated.

7.1.2 Theory

The main five phases of a backward handspring, earlier identified in Chapter 3, are as follows:

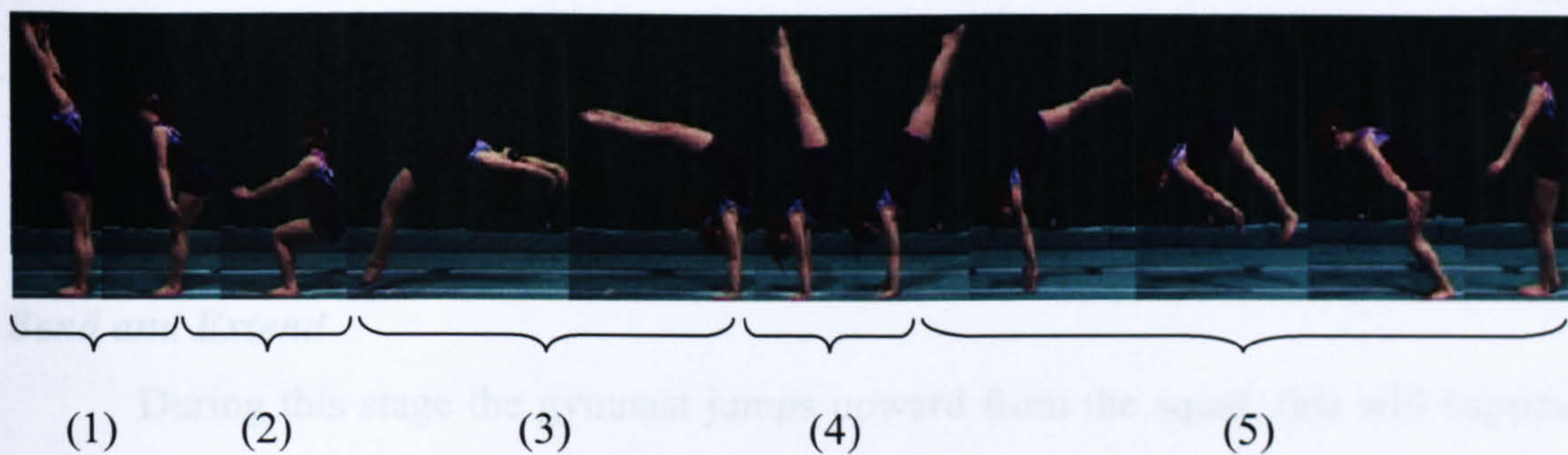


Figure 7-1: Paned image of a backward handspring.

1. Backwards fall to get the centre of mass behind the point of balance.
2. 'Bend and extend', jumping backward and upwards into the air.
3. First flight, from the feet to the hands.
4. Impact on the hands, the subsequent pivoting about hands, and the arch to dish 'snap'-action, and the arm push to initiate the second flight.
5. Second flight, from hands to feet, and landing.

A biomechanical analysis of the backward handspring was performed in order to establish what parameters affected each of the five phases. These parameters: linear velocity, rotational velocity, angle of contact with the ground, moments of inertia, components of force, and accelerations, will be used to describe performances of backward handsprings. Technical performance errors will be described using these parameters in order to provide a scientific understanding of the problem, and to provide quantitative comments as to how the performance can be improved.

Fall

The gymnast is required to fall in order to place the mass centre behind the base of support. In doing so the gymnast produces horizontal and vertical components of velocity.

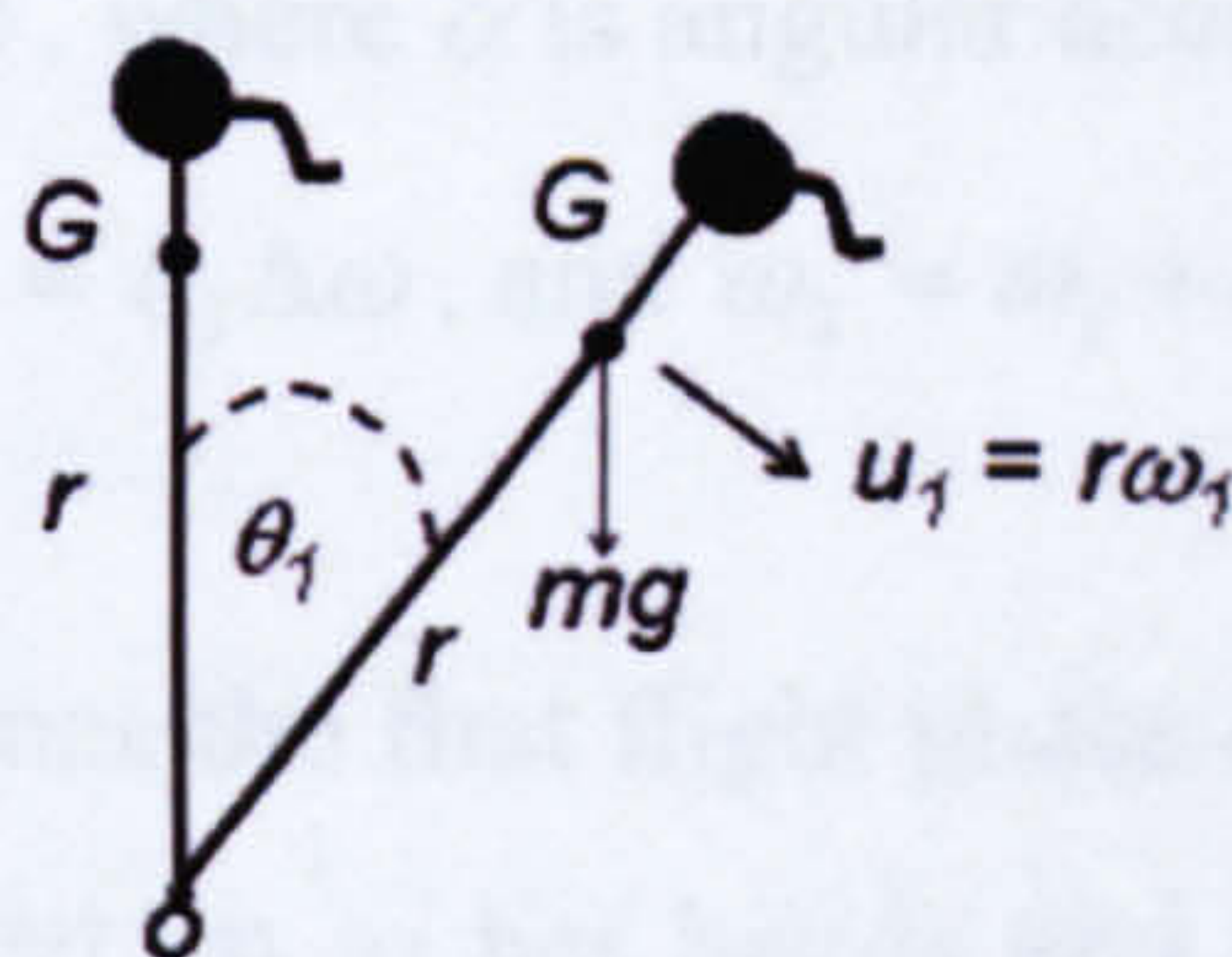


Figure 7-2: Phase 1 of backward handspring: the fall.

work done by gravity = gain in kinetic energy

$$mg(r - r \cos \theta_1) = \frac{1}{2} I_0 \omega_1^2, \text{ where } I_0 = [I_G + mr^2]$$

Bend and Extend

During this stage the gymnast jumps upward from the squat, this will happen in close succession to the 'fall', with some over-lap between the falling and squatting phases so that the angle from which the gymnast extends occurs at θ_1 .

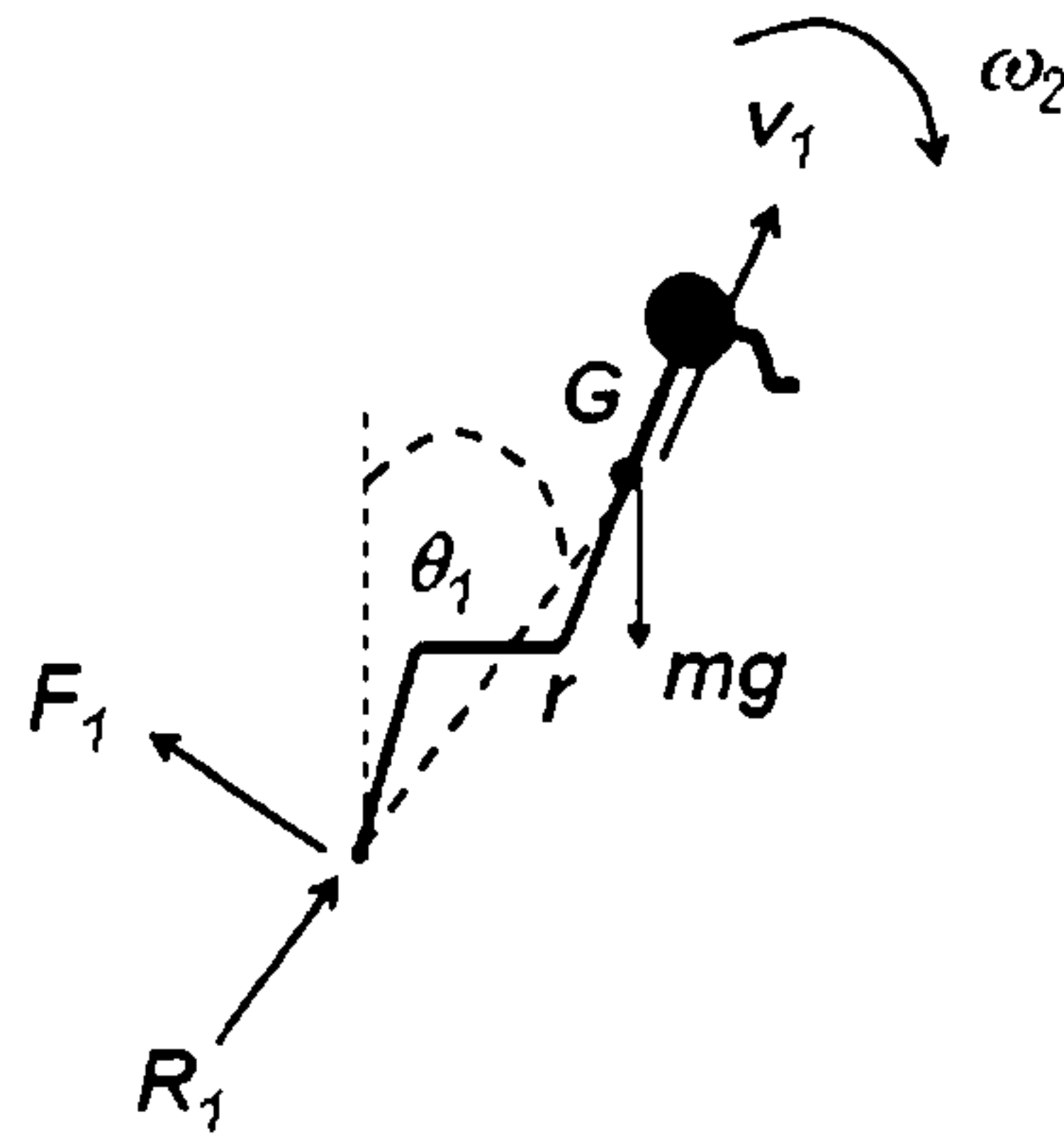


Figure 7-3: Phase 2 of backward handspring: the jump.

The force R_1 arises from the gymnast arching, and pushing back into the floor with the feet.

Applying Newton's 2nd Law:

$$R_1 - mg \cos \theta_1 = m(\ddot{r} - r\omega^2)$$

$$R_1 \Delta t - (mg \cos \theta_1) \Delta t = m\dot{r} - (mr\omega^2) \Delta t$$

impulse = change in linear momentum

$$R_1 \Delta t = m\dot{r} = mv_1$$

Taking moments about the mass centre:

$$F_1 r = I_G \alpha, \text{ where } \alpha \text{ is angular acceleration}$$

$$F_1 \Delta t \cdot r = I_G \Delta \omega, \text{ and } \omega_2 = \omega_1 + \Delta \omega .$$

Following the jump, comes the first flight phase of the skill. During this phase the gymnast jumps from her feet on to her hands and attempts to land in an arched handstand shape (Hayhurst, 1980).

Flight 1

During the flight, the gymnast must maintain a constant body shape. She will land safely onto her hands in the correct orientation and with the correct body configuration, so long as she has produced sufficient rotation and velocity in the previous two phases (1 and 2).

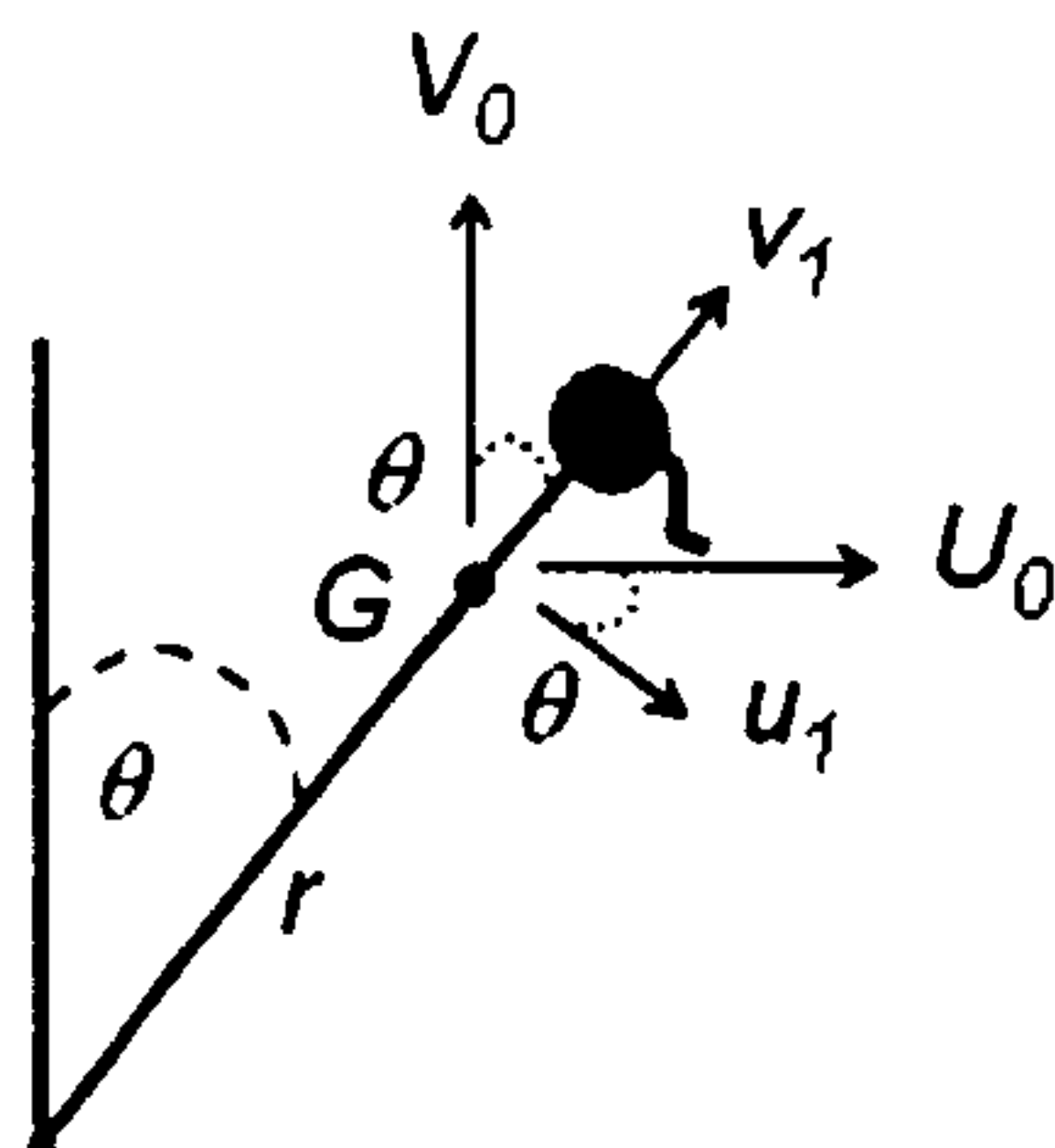


Figure 7-4: Phase 3 of backward handspring: first flight.

The gymnast is travelling in flight under constant acceleration due to gravity.

$$U_0 = u_1 \cos \theta_1 + v_1 \sin \theta_1, \text{ this remains constant during flight}$$

$$V_0 = v_1 \sin \theta_1 - u_1 \cos \theta_1$$

$$h = V_0 t - \frac{1}{2} g t^2, \text{ which gives } t \text{ on landing}$$

$$d = V_0 t, \text{ which will be the distance travelled by the mass centre during the flight.}$$

The angle through which the gymnast has rotated during flight is:

$$\Delta \theta = \omega_2 t$$

The angle of the gymnast when landing on the hands is defined as being the angle through which the gymnast has fallen through plus the angle which the gymnast has rotated during flight:

$$\theta_2 = \theta_1 + \Delta \theta$$

Impact

When landing on her hands, the gymnast must maintain an open shoulder angle (Boone, 1976) to provide a solid body configuration for the landing into the arched handstand position. During the time that her hands are in contact with the ground, the gymnast will rotate clockwise about her hands. V_0 and U_0 have the same values as in phase 3 if it is assumed that the mass centre remains at the same height above the floor on landing.

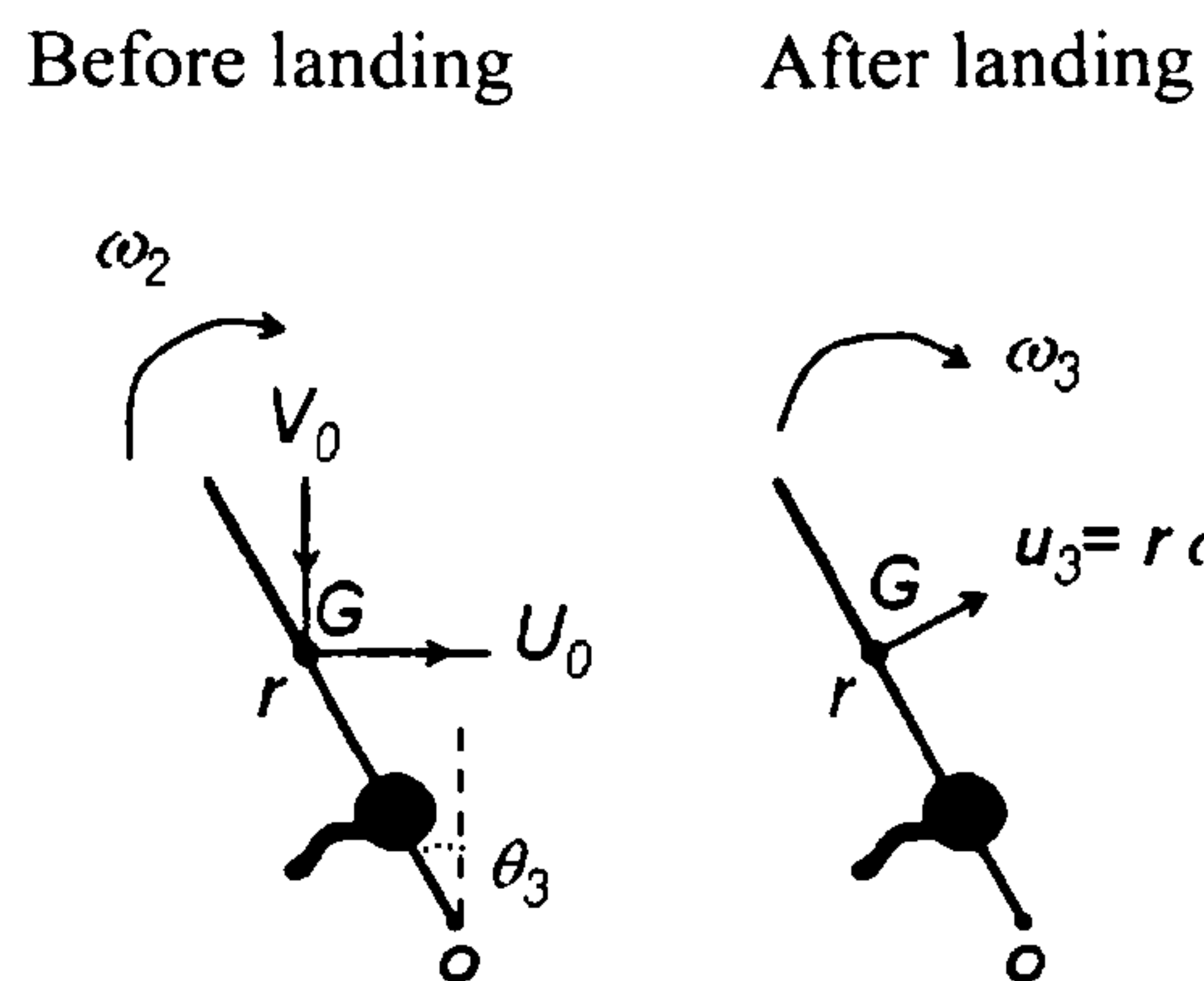


Figure 7-5: Phase 4a of backward handspring: impact and rotation about the hands.

For an instantaneous impact, the angular momentum about O will remain constant.

$$\theta_3 = 180^\circ - \theta_2$$

Taking moments about O:

$$mU_0 r \cos \theta_3 - mV_0 r \sin \theta_3 + I_G \omega_2 = mu_3 r + I_G \omega_3$$

$$mU_0 r \cos \theta_3 - mV_0 r \sin \theta_3 + I_G \omega_2 = [mr^2 + I_G] \omega_3, \text{ which gives } \omega_3$$

During phase 4, both phase 4a and phase 4b will occur in conjunction with each other. As the gymnast lands on her hands, and her body begins to rotate about her base of support, she will also be engaging muscles in order to rapidly change her body shape from an open arch to a closed dish in order to create rotational energy.

Snap Action

In the 'snap' (or reverse kip) action, the gymnast contracts her hip flexors, changing her body configuration from arched to slightly piked or dished. The result of this action is to increase the angular momentum in the post flight phase (Still, 1990).

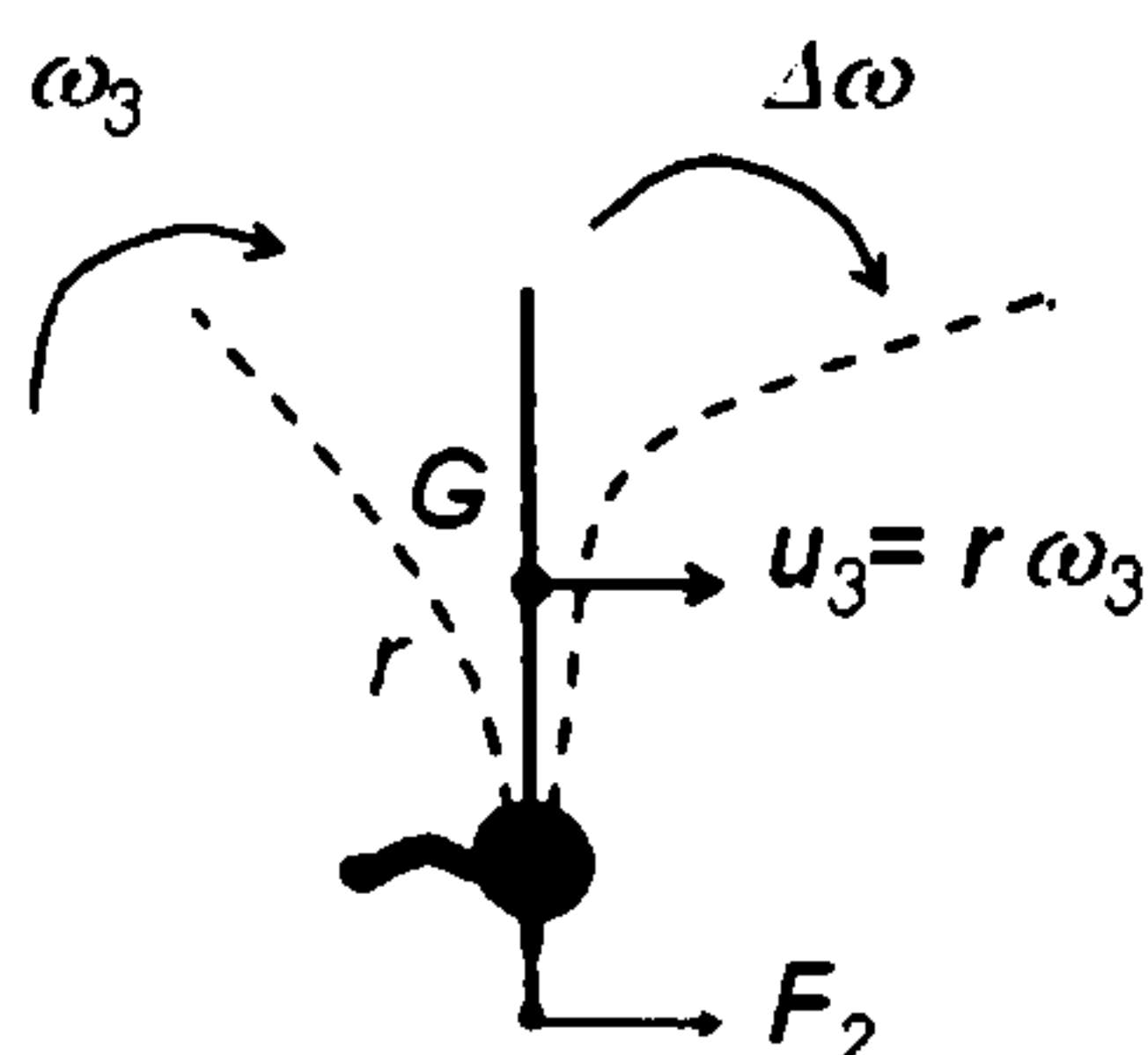


Figure 7-6: Phase 4b of backward handspring: arch to dish snap action.

During this action the backward reaction force F_2 is created as the gymnast pushes the hands forwards into the floor.

$$F_2 r = I_0 \alpha$$

$$F_2 \Delta t \cdot r = I_0 \Delta \omega, \text{ where } \omega_4 = \omega_3 + \Delta \omega$$

This phase is concurrent with the snap phase. To initiate the second flight phase of the skill, the gymnast also presses her arms into the floor to increase her vertical velocity.

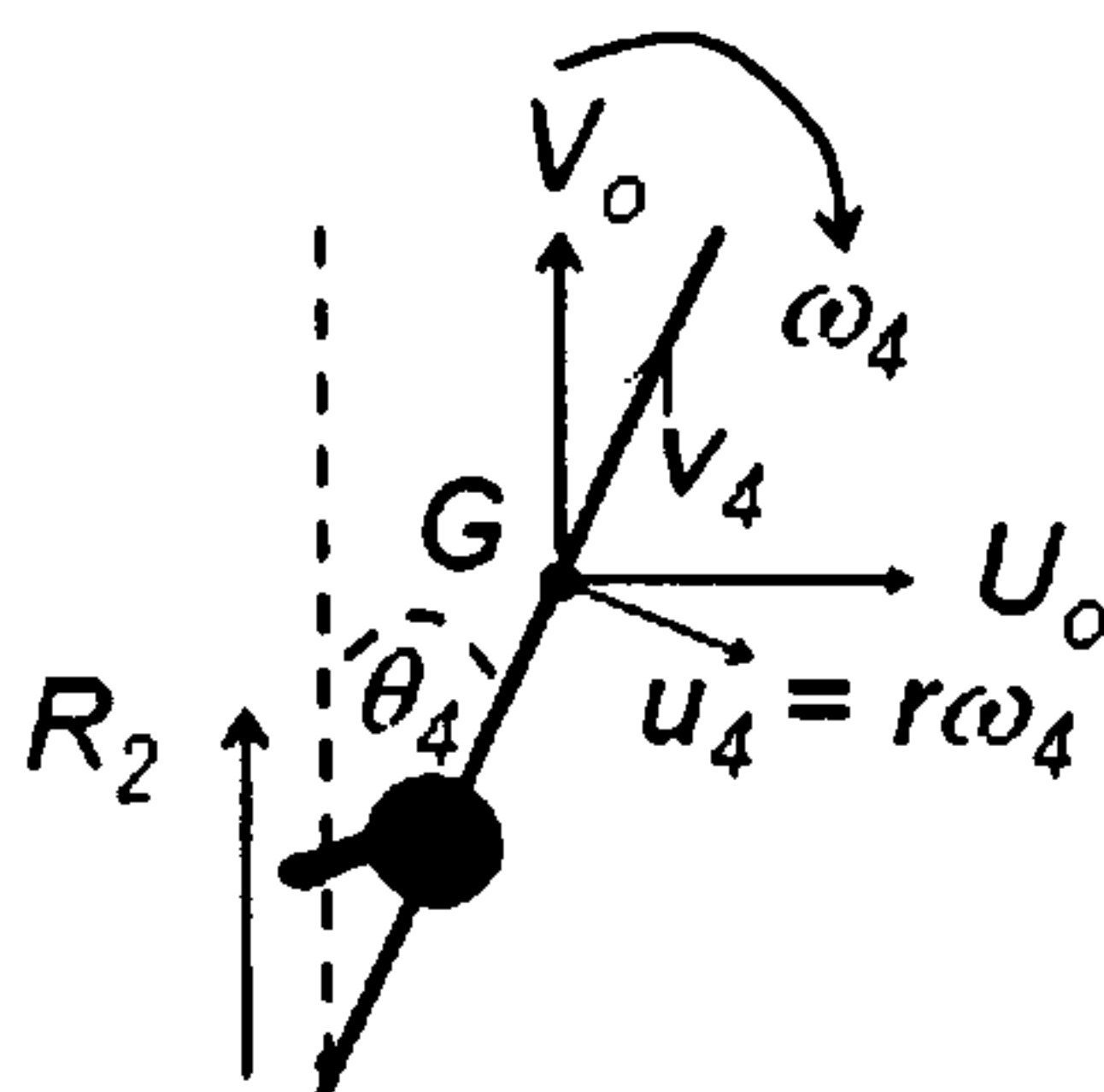


Figure 7-7: Phase 4c of the backward handspring: push phase.

The radial reaction force R_2 is generated through the gymnast extending the shoulder into the floor on take-off of the second flight phase.

Impulse = change in linear momentum

$$R_2 \Delta t = m v_4$$

Flight 2

During the second flight phase, the gymnast leaves the floor in a slightly dished shape, and rotates about the hip, landing back onto her feet. This is only possible if she has produced sufficient rotation and vertical velocity in the previous stage (phases 4 and 5).

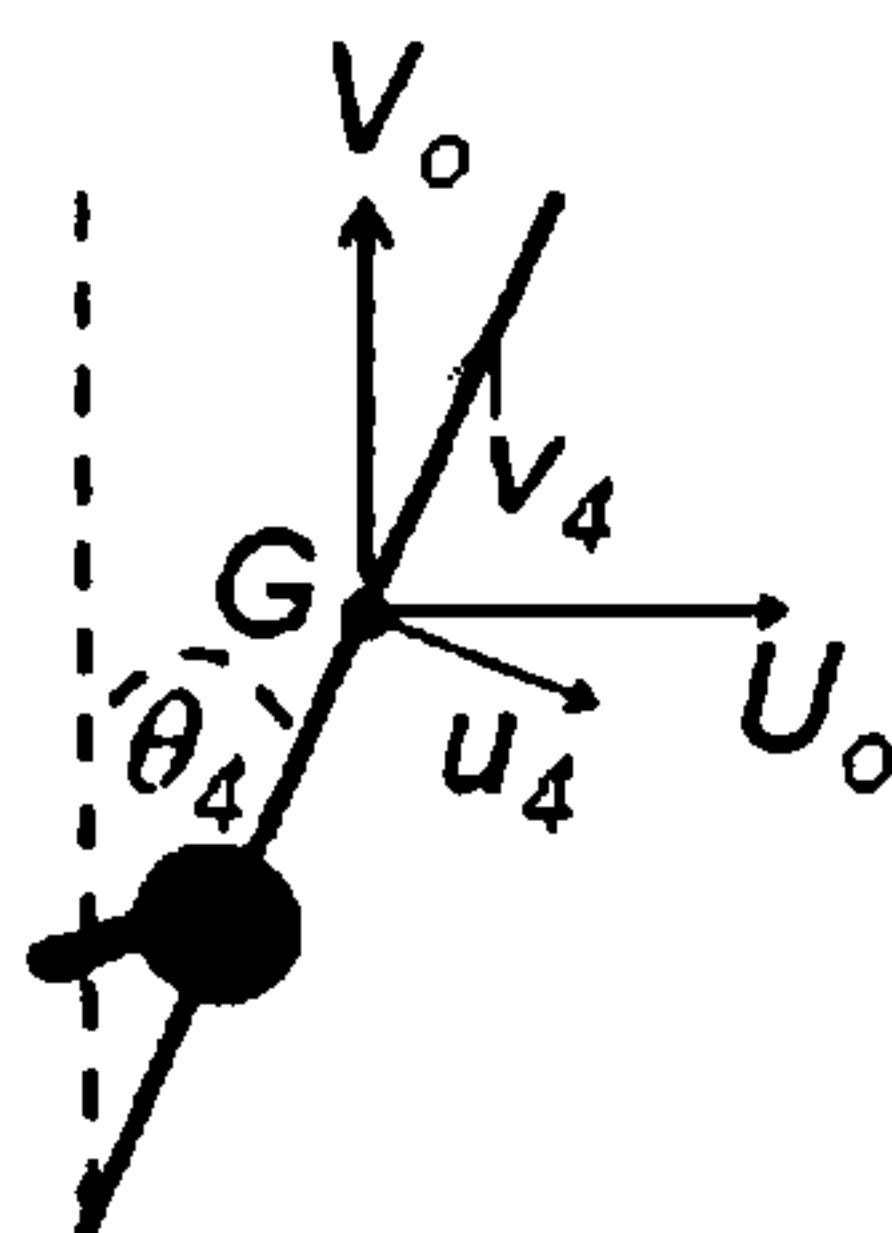


Figure 7-8: Phase 5 of backward handspring: second flight.

Once in flight the gymnast is travelling under constant acceleration due to gravity.

$$U_0 = u_4 \cos \theta_4 + v_4 \sin \theta_4$$

$$h = v_4 - \frac{1}{2} g t_2, \text{ this gives } t \text{ for the flight time}$$

$d = U_0 t$, which is the distance travelled by the mass centre during the flight.

The angle which the gymnast rotated through during the flight is:

$$\Delta \theta = \omega_4 t$$

The angle at which the gymnast will land on the feet is:

$$\theta_5 = \theta_4 + \Delta \theta$$

These equations will be used later in the study to explain differences between performances, and will also permit quantitative descriptions and comparisons of techniques of the individual stages of the backward handspring.

7.2 Data collection

This section will detail the methodology of the data collections performed. Experimental set ups will be described and analysis procedures will be discussed.

7.2.1 Introduction

There have been several studies carried out on the backward handspring. These have included take-off mechanics for somersaults out of the backward handspring (Kriel, 1996), investigations into ground reaction forces in the arms on landing during a backward handspring (Koh et al., 1992), measurements of EMG in the lower extremities during tumbling takeoffs (McNeal, et al. 2003), and the most relevant study which was a comparison of the forces present in three different backward handspring progressions (Gervais et al., 2004).

None of these studies have investigated the backward handspring with regards to learning, feedback or successful coaching techniques. There is therefore no predetermined method of data collection for this study.

7.2.2 Pre-testing

Coaching literature had shown that there were several different approaches to coaching the backward handspring, and that these different approaches involved the gymnast performing various different preparatory exercises before attempting a supported full skill.

Different angles of takeoff had also been recommended within the literature; for example Mitchell (2002) in a coaching manual suggested a takeoff angle to be 70° from the gymnast to the horizontal, in an anticlockwise direction, ($180^\circ - \theta_i$, in Figure 7.3), whereas Kriel (1996), reported measurements for the same angle within the range of 62° - 64° for a backward handspring prior to a back somersault.

During discussions with various coaches of different levels and disciplines, one relationship seemed to be prominent, and that was that the length of a standing backward handspring should be the same length as when the gymnast is laid on the floor with her arms out stretched. This however did not appear anywhere in any of the literature reviewed and so can only be considered loosely as a performance trend.

As no other data could be found on relationships between the height of a gymnast and characteristics of the backward handspring, it was decided that by videoing a backward handspring, and overlaying static images of the skill, different dimensions which would categorise the shape of the backward handspring may become apparent. These dimensions would become the performance parameters which would be investigated for a range of gymnasts in order to permit a suitable design of training aid.

Cameras

Cameras are frequently used in biomechanics to video activities for analysis. High-speed cameras can now collect data at 1000Hz, with high spatial resolution which has permitted more detailed research into sporting movements to take place. The most common means of obtaining movement data in sports biomechanics has been the manual digitising of film or video recordings. Many sporting movements which may appear to be essentially two-dimensional in nature require three-dimensional data collection techniques if their full features are to be revealed. Three-dimensional analysis however generally requires two or more cameras to be used for sufficient data to be collected to permit a 3-D reconstruction to take place (Yeadon and King, 1999). The accuracy of measuring human movement is highly dependent upon the accuracy of the method used to record it. Calculated kinematic values of

subjects rely heavily on the accuracy of the motion data collected from the subject, and the accuracy of video data recorded must be as precise as possible if any future movement analysis is to be accurate (Kennedy et al., 1989).

7.2.3 Pilot Study

Preliminary Data Collection

From the descriptions and diagrams in the literature reviewed, and from observations of gymnasts performing backward handsprings, it was hypothesised that a volume would remain free under the gymnast during the performance of the skill. It was anticipated that this volume would have a side profile of an arc as was described in Kriel (1996), and in Bennett and Miller (2001), where the body during this stage of the skill was described as a long ‘rainbow’ shape.

Video was taken of a National level Sports Acrobatic Gymnast, and using Dartfish, a sports video analysis program, a strobe-overlaid image of the performance was created (Figure 7.9).



Figure 7-9: Pre testing the backward handspring.

As can be seen from the overlaid video sequence in Figure 7.9, the shape of the ‘free volume’ beneath the backward handspring is in fact not an arc. Due to the ‘sit’ during the ‘bend-extend’ phase at the beginning the skill, the hips and torso encroach into the arc shape, producing what will be described as an *igloo* shape. It is accepted that the shape of the *igloo* will vary between gymnasts, but the performance in the image above only received a 0.5 deduction when scored by an International judge, thus only

minor errors were observed (F.I.G. 2006 Code of Points); consequently this will be assumed to be a good *igloo* shape.

7.2.3 Pilot study

It was decided that further video should be taken to confirm the presence of the *igloo* shape as a free volume beneath the backward handspring, and to ensure that all data required could be collected from the digital video. The volume was first calibrated using marked poles which were videoed within the capture volume (Figure 7.10). This was to permit the calculation of a pixel: mm ratio for measurements to be taken on performance parameters of backward handsprings. This calculation was possible as the position of the white calibration balls were measures accurate to 1mm, and the positions of the white balls were also measured in pixels from the digital image. The two sets of measurements were then compared to calculate the ration of pixels to millimetres.

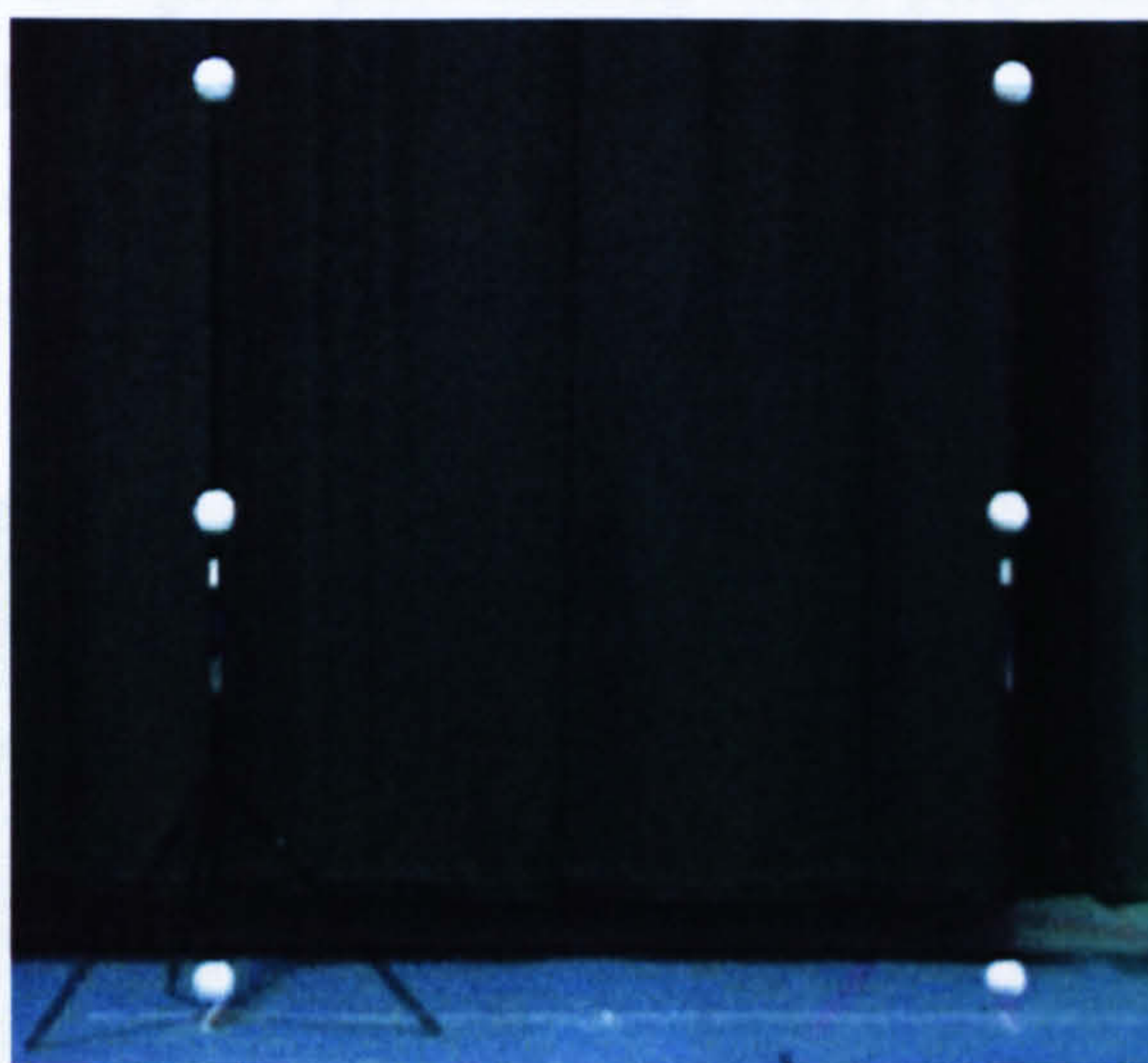


Figure 7-10: Calibration poles positioned within the capture volume.

The images below (Figures 7.11 and 7.12) show two different gymnast performances of backward handspring. The performance in the left image received a 0.0 penalty when assessed by an International judge, and the right performance received only a 0.3 penalty. The right image however shows that the gymnast performed a very loopy backward handspring which although technically good to the judge's eye, and showed good rebound, was actually high and short, and these are not redeeming characteristics of a good standing accelerator backward handspring. They

are however required characteristics of a standing beam backward handspring, and so would not necessarily be classified as deductions by a judge. For a backward handspring to be deemed as loopy, with reference to Figures 7.2 to 7.8, the gymnast will have executed a high short performance, which generally has a lack of dynamic content (Hay, 1993), due to a small V_0 and θ_1 value but a large ω_2 . This style of backward handspring can be performed intentionally, as on the beam when it enables the gymnast to see and spot the beam early. It can however also be performed due to lack of good technique. In this situation a gymnast will normally have pushed the knees forward on takeoff, reducing the height of the mass centre, r , and reducing the reaction force F_1 . This poor technique often then results in the skill being under-cut in the first flight, with the hands too close to the position from where the feet took off, making θ_3 negative, and placing the mass centre on the wrong side of the hands, hence reducing R_2 . This produces a ‘gainer’ action which is not good technique for a standing accelerator backward handspring.

This action will have to be taken into consideration when assessing which future performances are ‘good’ performances. Only performances which receive a deduction of ≤ 0.5 (the skill was judged out of a value of 1.0), from an International judge, and which also when strobe-overlaid show an adequate *igloo* shape will be used for future analysis unless otherwise stated.



Figure 7-11: Good *igloo* shape.



Figure 7-12: Poor *igloo* shape.

To enable the design of a training aid for the backward handspring, research had shown that specific lengths and heights of a performed skill would be required. This was to permit the design of a structure which would not encroach into the space

in which the skill was performed, but would only fill the free volume beneath. It was decided that digital video would be collected on multiple gymnasts in order to achieve this.

It was established, that it was possible to obtain all the measurements required for the study from the digital video. As only 2-D planar motion was to be considered, using graphics packages which output a pixel position, the measurements required could be acquired directly from the images obtained from the digital video.

From the images produced, and from information extracted from the reviewed literature, seven performance parameters were established, which were considered important in designing a prototype training aid (Figure 7.13). These seven measurements would be calculated for each performance from the main data collection.

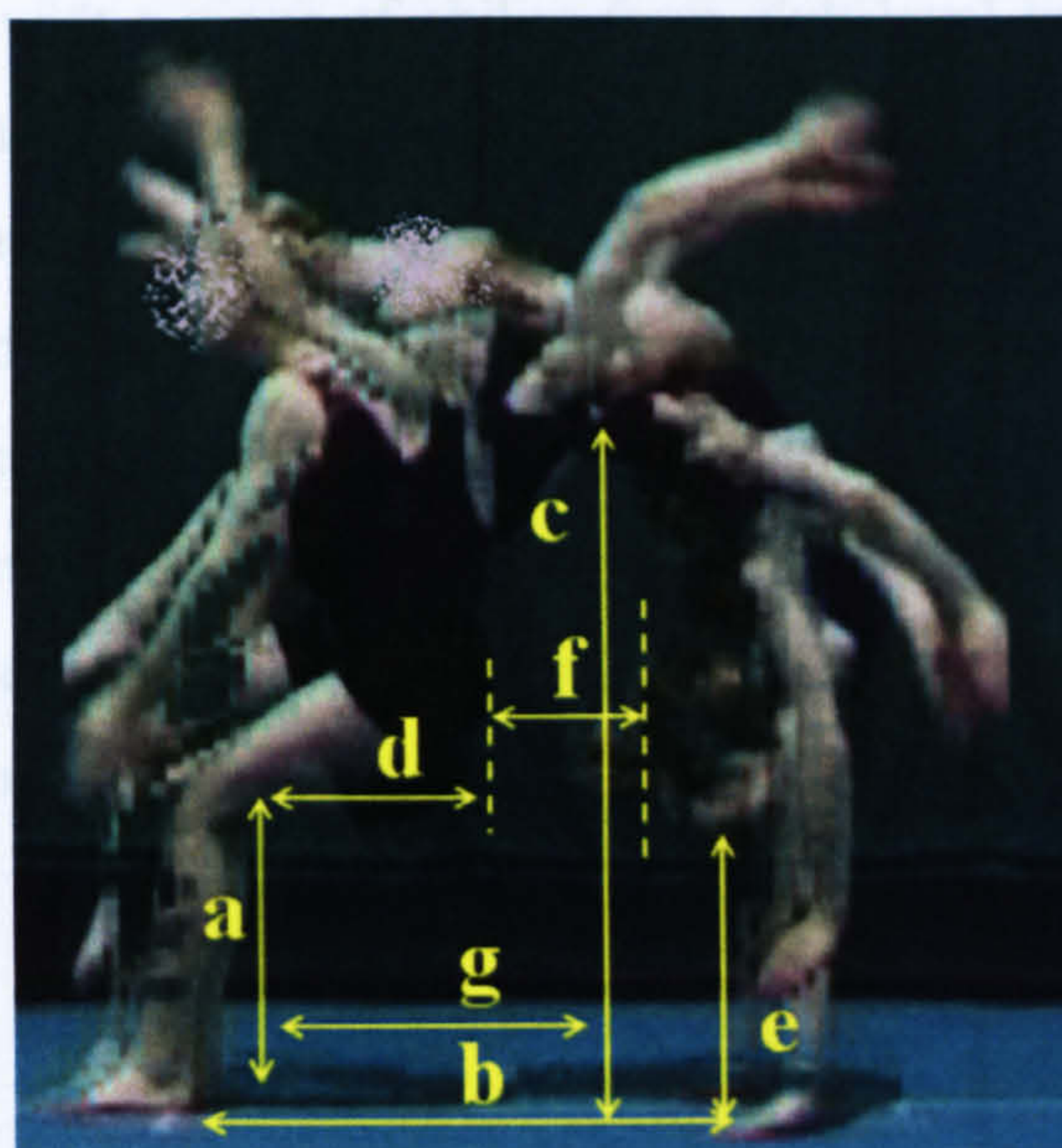


Figure 7-13: Seven performance parameters of the backward handspring.

The dimensions are as follows:

- a – Height of the sit.
- b – The distance from the heels to the finger tips.
- c – The maximum height of the arch.
- d – The length of the sit.
- e – The distance the head is from the floor.
- f – The distance from the back of the hips in the sit to the back of the head.
- g – The position from the back of heels to the point at which the maximum height of the arch occurs.

7.2.4 Backward handspring data collection

Before any data was collected, coach and parental permission were obtained for each participant. During the data collections the coaches of the participating gymnasts were present, along with two researchers, one male and one female.

Main Data Collection Methodology

The gymnasts involved in this data collection were from several different disciplines and from two different performance levels. The majority of the participating gymnasts were registered on British Gymnastics World Class Start programs, and were all elite gymnasts. From these squads, there were members representing Men's Artistic Gymnasts, Women's Artistic Gymnastics, and Sport Acrobatics Tumbling. Besides these gymnasts, data was also collected on a range of club level gymnasts, with a range of ability from club level to Regional level, both males and females. In total data was collected on forty-one gymnasts.

All performances were filmed in the Loughborough University Gymnastics Centre with a standard 50Hz digital video camera, with a shutter speed of $600\mu\text{s}$. The collection area was calibrated before any performance data was collected, and the position of the camera and calibrations poles relative to the capture volume was measured and recorded for each separate filming session. The measurements that were taken are described in Figure 7.14.

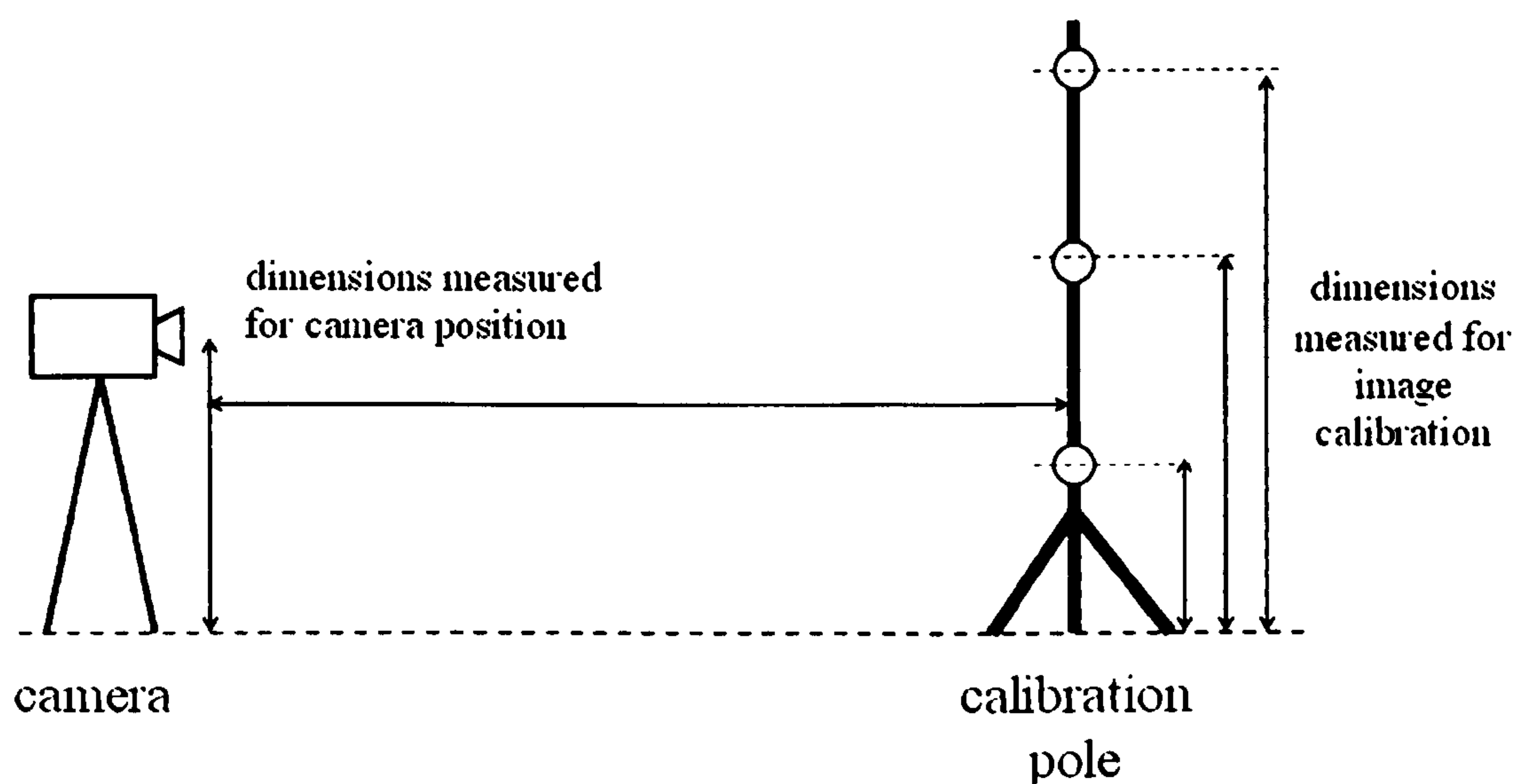


Figure 7-14: Camera set up for the data collection.

Each gymnast performed a one-legged static stance as can be seen in Figure 7.15, in order for limb measurements to be taken during the analysis of the video.

This was followed by two flexibility positions, a bridge (Figure 7.16) and a D-lumbar (Figure 7.17), which were executed in order to permit the analysis of potential relationships between back, hip and shoulder flexibility and the performed techniques of the backward handspring. The gymnast was then asked to perform a single 'good' two footed standing backward handspring, landing with feet together. If they were unhappy with the performance, it was allowed to be repeated. The final stage of the data collection was to obtain heights and weights of all participant gymnasts.



Figure 7-15: Static stance position.

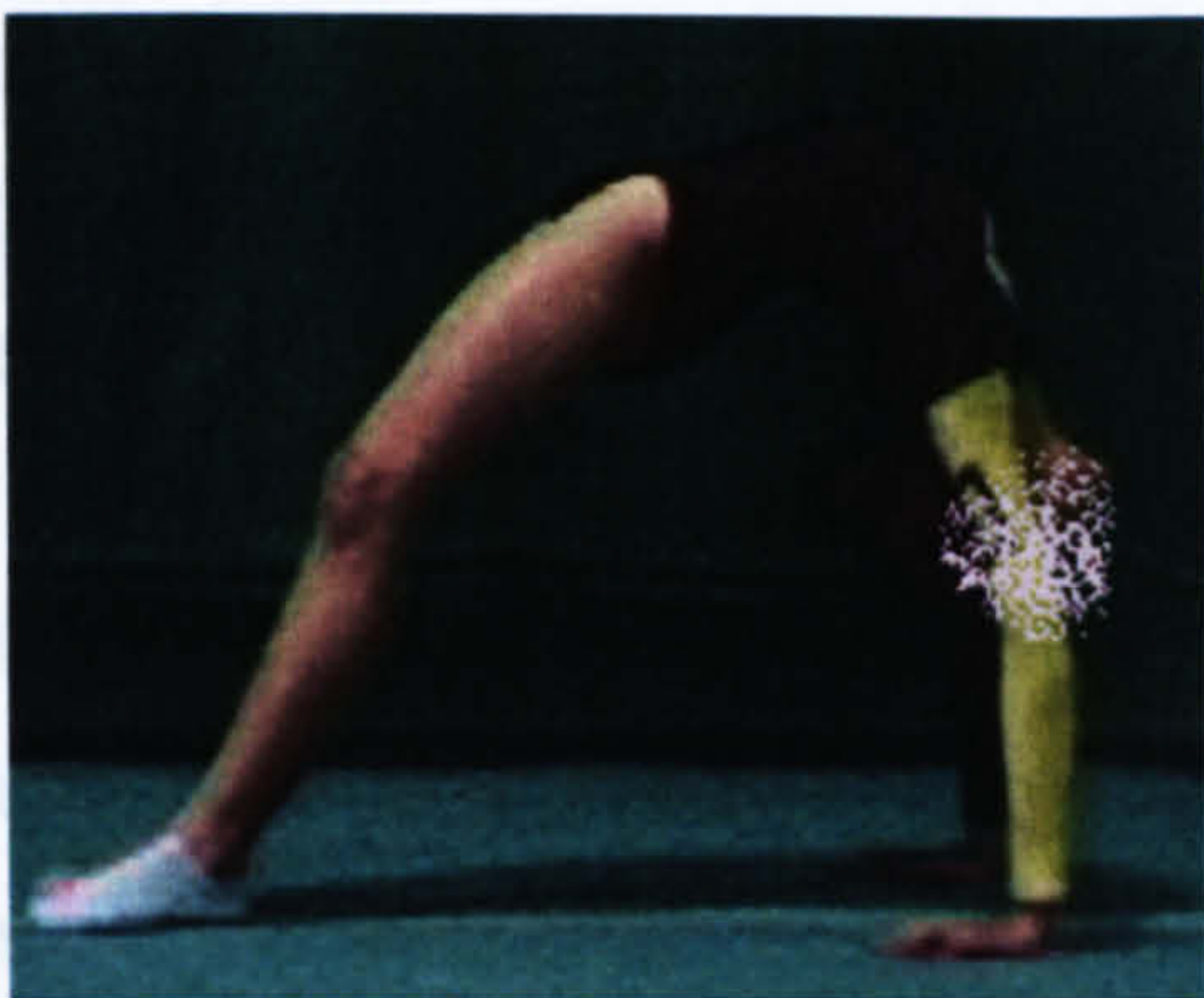


Figure 7-16: Bridge.

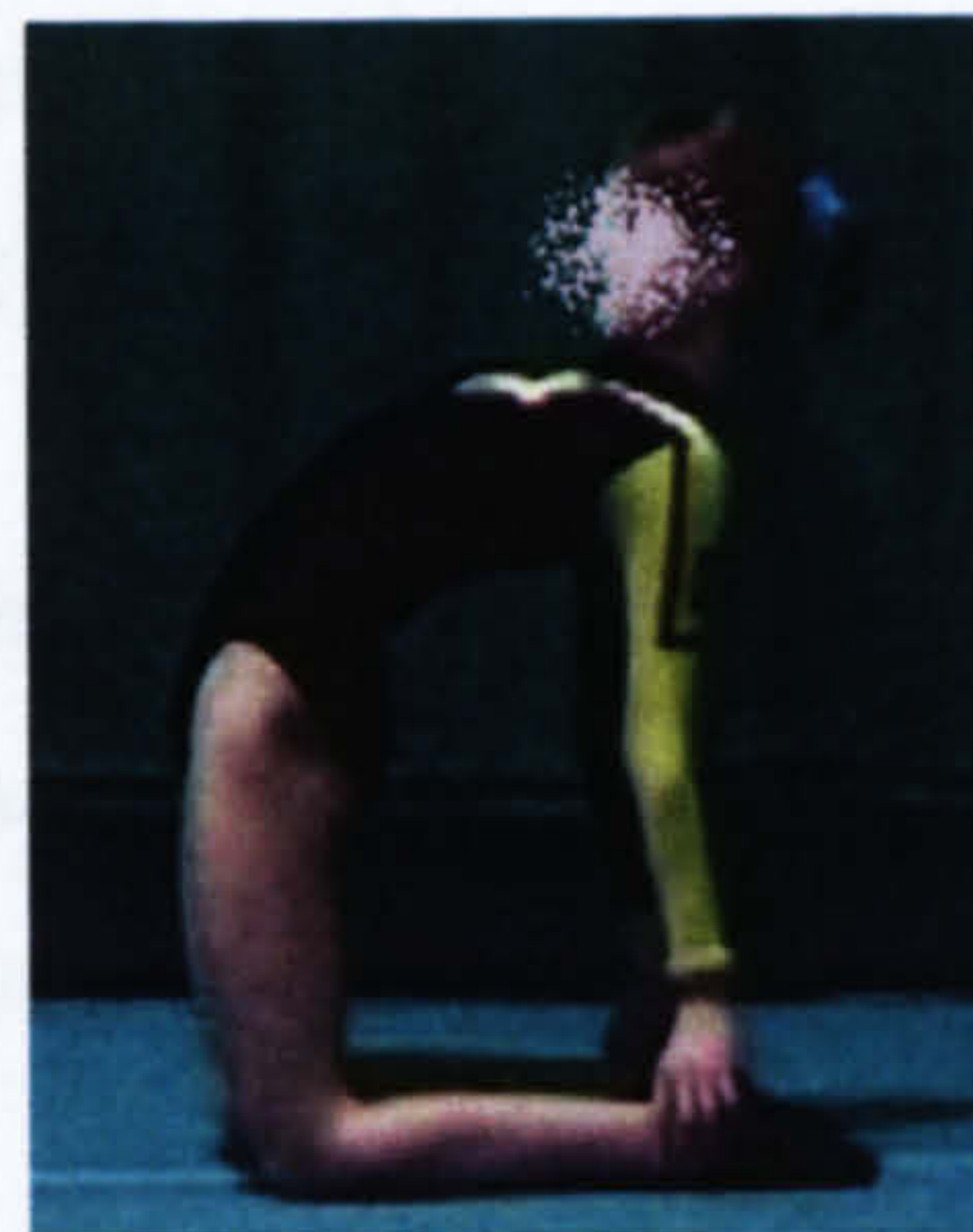


Figure 7-17: D-Lumbar.

Each of the performed backward handsprings was judged by an International judge. Each skill was processed using Dartfish, and images of the separate skills executed were created, including an overlaid image of the backward handspring performed by each gymnast. Performed backward handsprings which although when judged were considered good, if they had an incorrect *igloo* shape were then also rejected for performance parameter correlation work.

Using the calibration measurements a pixel-mm ratio was obtained. This permitted specific measurements to be taken from these images for each remaining individual gymnast. The data extracted comprised the height of the gymnast, measurements of each of the seven performance parameters, arm and leg length, and a flexibility rating for the hip, shoulder and back.

(1) It is hypothesised that the seven performance parameters will have a relationship with the height of the gymnast. It is possible that better correlations will be found from relationships between the performance parameters and leg or arm length, so this will also be investigated.

(2) It is also hypothesised that back, shoulder and hip flexibility may affect the shape of the backward handspring, making it higher and loopier. This will also be analysed.

7.3 Data analysis

The data obtained previously in Section 7.2 was compiled. In this section, the data will be evaluated and analysed, relationships and trends will be described, and theories will be discussed. Fifteen gymnasts from the original forty-one remained in the investigation at this stage.

It was decided that the measured distance between the head of the gymnast and the floor during the inverted landing on the hands (performance parameter 'e') would be a function of the gymnast's arm length, and so would not be incorporated during statistical analyses.

7.3.1 Statistical analysis of hypothesised relationships

Each of the six remaining performance parameters, were graphed against gymnast height, and leg length. It was considered that gymnast arm length would not produce any useful relationship with regard to evaluating relationships for the design of a prototype. From these graphs, the line of best fit was produced, and the R^2 value for the fit.

Hypothesis 1

As can be seen from the information in Table 7.1, there was a better correlation produced when regressing the performance parameters against the stature of the gymnast, rather than against the measured leg length. All further statistical analysis was therefore carried out using the standing height of the gymnast rather than the leg length.

Table 7-1: R² values for initial correlations

Performance parameters	R ² value for Standing height	R ² value for Leg length
a	0.63	0.65
b	0.42	0.46
c	0.89	0.87
d	0.24	0.21
f	0.49	0.34
g	0.35	0.31

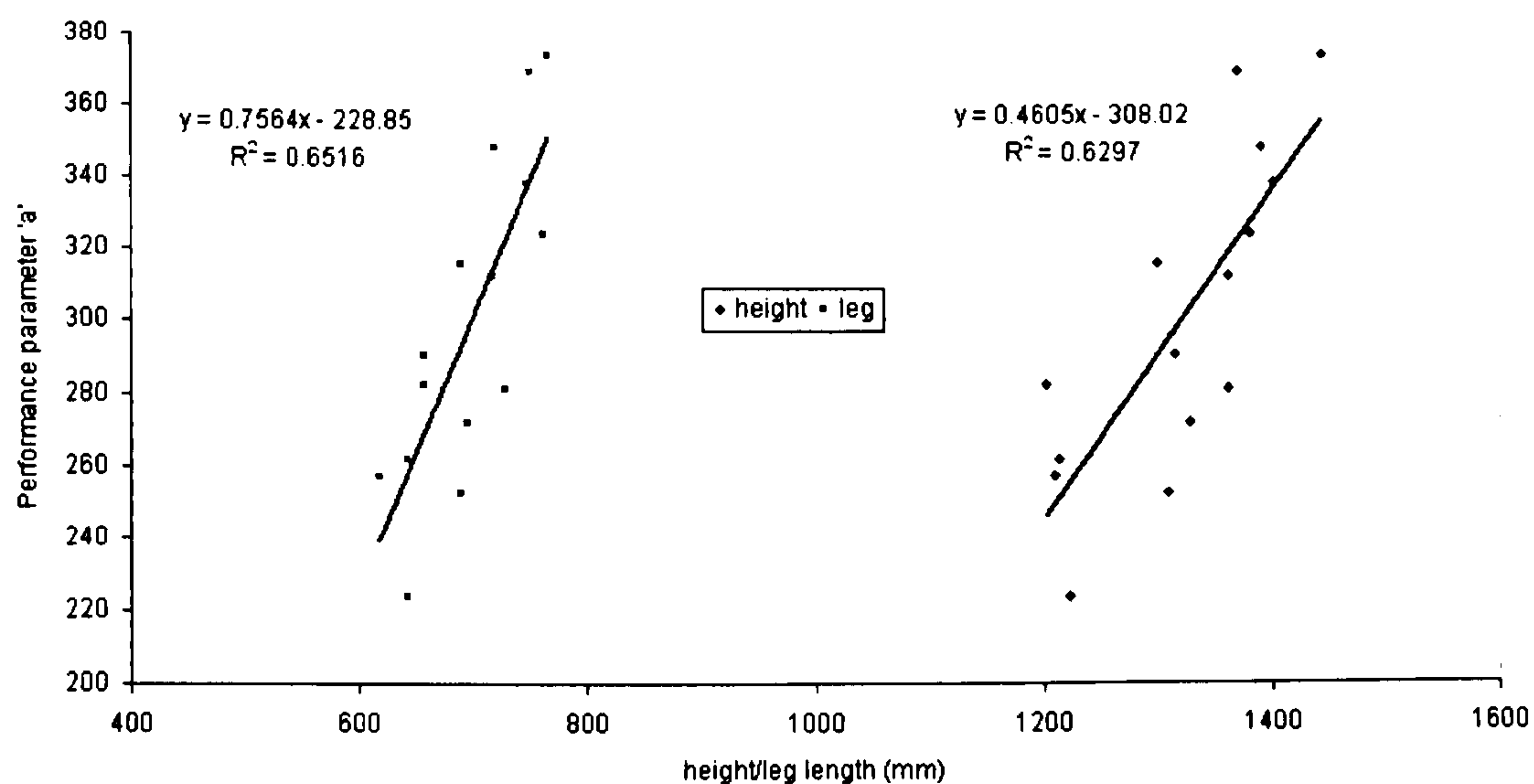


Figure 7-18: A graph of the correlations between standing height and leg length for performance parameter 'a'.

Graphs for the other performance parameters can be found in Appendix F. Following this decision, a statistical ANOVA analysis was performed on each of the remaining proposed relationships between the sustained performance parameters and the standing height of the gymnast. The following results were obtained and have been compiled in Table 7.2:

Table 7-2: Statistical analysis of performance parameters

Performance parameters	R ² value for Stature	Significance p	Standard error of the mean (mm)
a	0.63	0%	28.1
b	0.42	1%	56.3
c	0.89	0%	28.8
d	0.24	6%	29.7
f	0.48	1%	56.9
g	0.35	2%	51.9

As can be seen from above all of the relationships analysed were found to be significant at the 2% level, apart from *d* which is not significant until the 6% level. Although not all of the R² values of fit for the performance parameters were particularly close to 1, when considered alongside the significance of fit (*p*), all the relationships were considered to be valid.

Hypothesis 2

To analyse the effects of flexibility on the shape of the backward handspring, all forty-one of the trials were considered. The ratio of the maximum height of the arch in the backward handspring (performance parameter 'c'), and the length of the first phase of the backward handspring (performance parameter 'b') was calculated. This ratio was used as a description of how 'loopy' the backward handspring was, and was then correlated with the flexibility of the shoulder, hip, and back. No significant correlation was observed.

The hypothesis had been that a flexible gymnast would perform a loopier backward handspring, and correspondingly that inflexible gymnasts would execute a longer skill. This hypothesis however has been found to be insignificant for the data collected. It has been established that the majority of the gymnasts present at the data collection were well-conditioned and flexible. There is therefore a high probability that even though a more flexible gymnast may naturally perform a loopy backward handspring, with appropriate conditioning and training such gymnasts are as capable of performing a long dynamic backward handspring as an inflexible gymnast. Similarly inflexible gymnasts are as capable of performing a short backward handspring as a very flexible gymnast. This is due to factors such as pushing the knees forward during takeoff, and undercutting the skill when the hands land too close to where the feet took off.

7.3.2 Summary and design considerations

Relationships between six backward handspring performance parameters were each correlated against standing height and leg length (Table 7.1). All relationships were found to be significant, but better correlations were generally found between standing height than were found with leg length (a -3% lower, b - 9% lower, c - 2% higher, d - 13% higher, f - 31% higher, g - 12% higher).

Although the relationships between performance parameters (a to g) and standing height were found to be significant (a, $p = 0\%$; b, $p = 1\%$; c, $p = 0\%$; d, $p = 6\%$; f, $p = 1\%$; g, $p = 2\%$ significance), it was decided after further deliberation that some of the performance parameters were not critical. For a dimension to be considered critical, it must be a crucial dimension for the design of the training aid, rather than just a description of the skill.

It was observed that so long as the training aid was not designed to be longer than $(d + f)$, (Figure 7.13) to ensure that the gymnast's head would not hit the training aid, then the parameter b (distance between heels and fingers) would become redundant as the training aid would not physically be as long as this parameter.

It was therefore decided that the dimensions that were critical for the design purpose were the sit position (d, a) and maximum arch height position (g, c) (Figure 7.13). The positions of the head and fingers were still important, but as it was decided that the design would not encroach into this general area, a relationship was not required for the training aid to be designed, just a minimum value.

Finally, no significant relationship was found between flexibility and skill length, and so it was deemed possible to use the determined relationships between standing height and the performance parameters to design the training aid.

In the following chapter (Chapter 8) the relationships found in this chapter for the four remaining performance parameters (a, c, d and g) will be extrapolated for a wider range of gymnast statures. This is to establish the required values of the performance parameters for a range of gymnasts. From these values, decisions will be made with regard to design dimensions and equipment size variability.

8

Backward Handspring Training Aid Design and Manufacture

8.1 Introduction

This chapter will detail the design procedure undertaken during the development of the backward handspring training aid. It will also describe specific areas of the design which were critical to the success of the training aid. Calculations and diagrams will be used to justify the final design for the prototype training aid. Full 3-dimensional model drawings of the training aid can be seen in Appendix A2.

8.2 Design path for a backward handspring training aid

Before the conceptual stage of the design could be started, it was important to identify crucial components of a prototype training aid to support the backward handspring. This was performed as described in Chapter 5, by expanding the generic design path detailed in Chapter 3, and making it specific to the backward handspring. This was achieved also using the same method detailed in Chapter 5, whereby information about the backward handspring, crucial stages of the skill and technique, and different supporting options obtained from the reviewed literature and from surveyed High Performance Coaches, was collected and combined within a new design path. This backward handspring specific design path can be seen below (Figure 8.1)

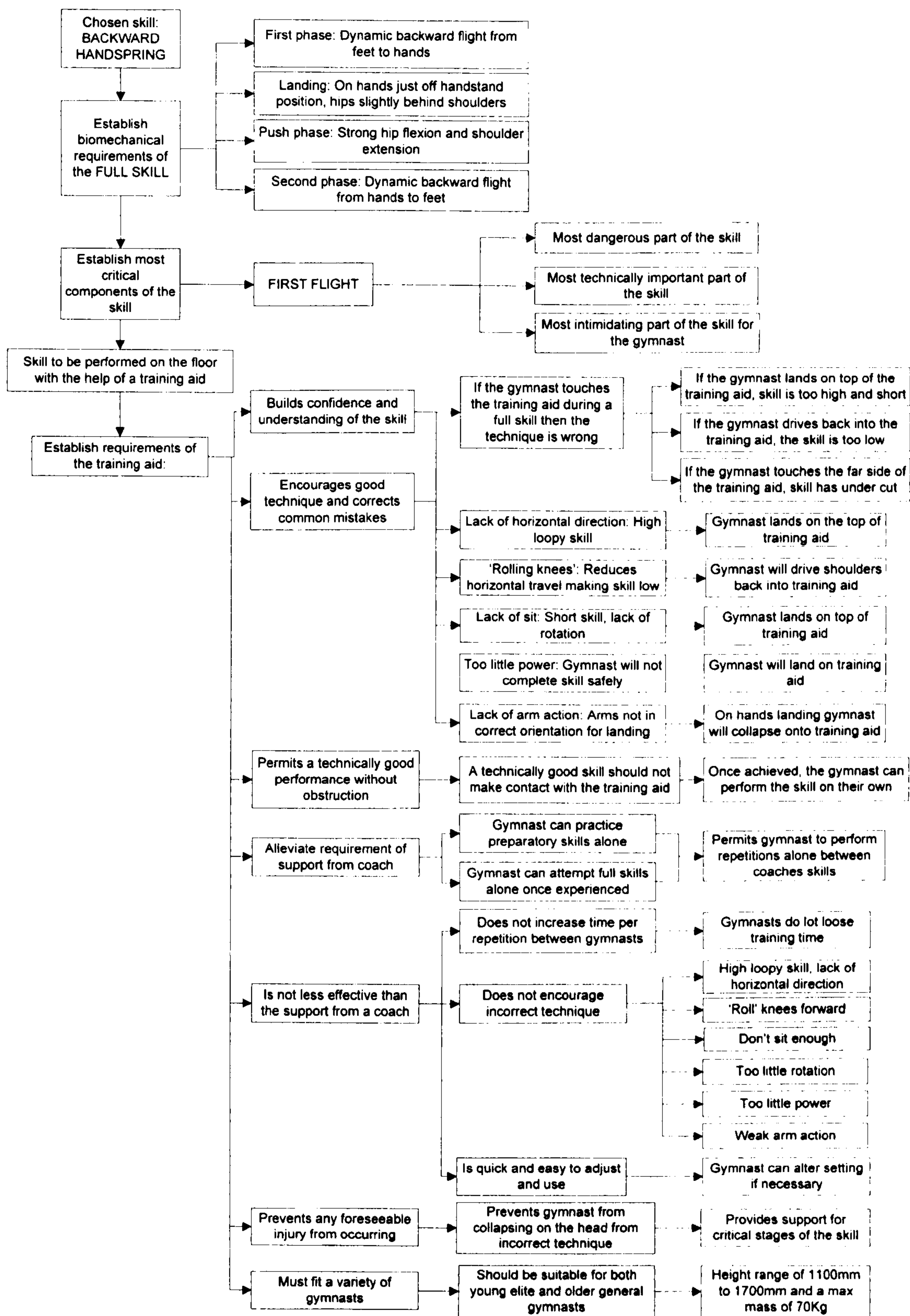


Figure 8-1: Design path for a training aid to help teach a backward handspring.

8.3 Product design specification

As in Chapter 5, from the initial customer requirement tree, in addition to interviews with High Performance Coaches, and from the reviewed literature it was possible to produce a fully detailed requirement tree (Appendix B2) making it then feasible to construct a complete Product Design Specification (PDS) (Appendix C2). From the details held within the PDS it will be now possible to develop a design that will accomplish all of the criteria for a training aid to support a backward handspring.

The PDS as in Chapter 5, contains specific information for this particular training aid, such as British Standards requirements, loading limitations and environmental conditions. It also contains the customer requirements, anthropometric considerations, and performance criteria. It will be crucial that the design for prototype meets the demands of the PDS.

8.4 Design process

The method and process utilised for the design of the backward handspring training aid will be discussed in detail within this section of the chapter. Supporting calculations and diagrams will be detailed in order to clarify decisions made during this process.

8.4.1 Design data from testing

From the data collected in Chapter 7 the four critical performance parameters were determined to be: sitting position - parameters d and a , and the maximum arch height position - parameters g and c (Figure 8.2).

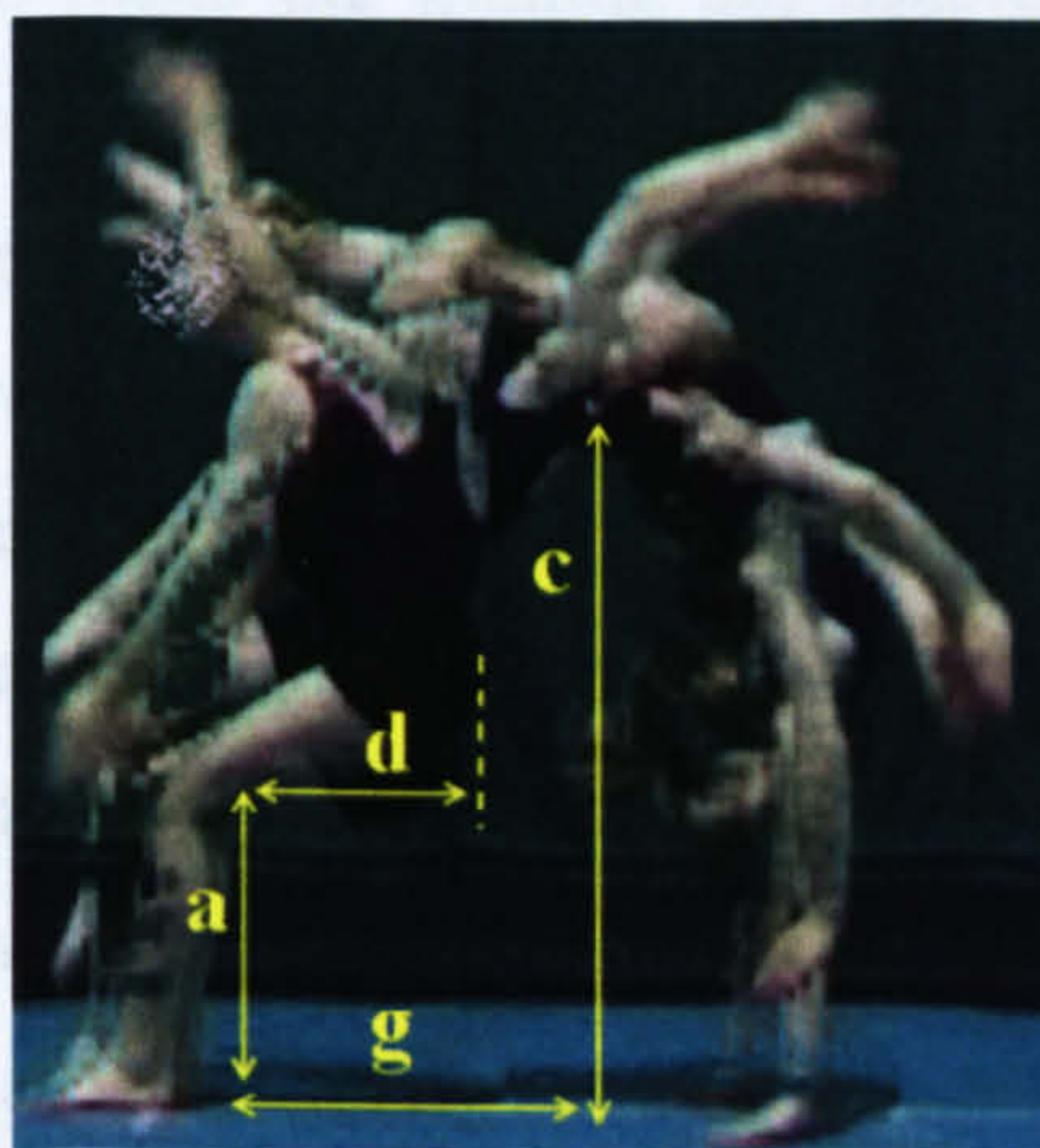


Figure 8-2: Performance parameters.

For design purposes, it was required that this data set be extrapolated so that the information obtained covered the required range of standing heights (Table 8.1) for male and female gymnasts (detailed in the PDS, Appendix B2). This was performed by producing an equation for the line of best fit, and then extrapolating to produce the required data for the heights not covered in the collected data set, which spanned 1203-1440mm.

Table 8-1: Extrapolated performance parameter data

Standing height	a	c	d	g
1100	199	518	267	376
1200	245	621	288	424
1300	291	724	308	472
1400	337	826	329	520
1500	383	929	350	568
1600	429	1031	371	616
1700	475	1134	391	664

From these data, intermediate standing heights were also found using interpolation so that the data was in thirteen 50mm increments. To enable the training aid to be 'user friendly', it was decided that there should be three specific settings of the training aid: small, medium and large. It was therefore important to establish how to divide the standing heights into groups to fit the three settings, and if it was possible to produce only three settings from the range of thirteen standing heights. To determine this, the standard error of the lines of fit for the performance parameters, and the incremental increases in the performance parameters were considered.

It had been established that the training aid must be designed so that it was possible to perform a good backward handspring over the training aid without making contact with the equipment. Therefore to make the training aid usable it must be ensured that the smallest gymnasts within the standing height group could clear the training aid according to the determined dimensions, as taller gymnasts could use the subsequent setting if required. As the standard errors of the linear fits to the four performance parameters were quite high (28-52mm) as discussed in Chapter 7, and they were of similar magnitudes to the increments of the performance parameters (10-50mm) between the thirteen standing heights, it was deemed possible to group the thirteen standing heights into the required three settings (Table 8.2) of which the bold text rows were the dimensions for that height category. This was possible as the standing height range within each category was within the boundaries of the chosen dimension plus or minus the standard error; e.g. for performance parameter g in the smallest setting: 400mm – 50mm = 350mm which is less

than the required 370mm and $400\text{mm} + 50\text{mm} = 450\text{mm}$, which is just over the required 448mm for this height setting.

The standing heights that the adding and subtracting of the standard error did not always cover were the band between the standing height settings, i.e. 1250 – 1300mm and 1450 – 1500mm, but as the standard error was large, it was established that it would be hard to predict whether a particular gymnast would require the taller or shorter height setting. It could be argued however that one of the settings would be suitable for each of the gymnasts who fell within this boundary, and so the method of the division of the standing heights into three categories was maintained.

The one group of gymnasts that this separation category method did not cover was the smallest gymnasts (1100mm) if performing the skill still within the standard error of the data, but at the lowest possible skill height (e.g. for 'c' $520\text{mm} - 50\text{mm} = 470\text{mm}$, 100mm lower than the design height of 570mm), it is possible that such gymnasts may not be capable of clearing the training aid. It was however deemed unlikely that the majority of gymnasts would fall into this criteria as only few gymnasts learning the skill would be only 1100mm tall, and so the training aid was to be designed to have only three height settings. The feasibility of this design choice would be tested practically later, after the manufacture of the prototype. Extracting, and then rounding the dimensions in Table 8.2 to the nearest 10mm for simplification of the design process gave the data set in Table 8.3.

Table 8-2: Division of heights into three size categories

		Standing height (mm)	a (mm)	c (mm)	d (mm)	g (mm)
Small		1100	200	520	260	370
	*	1150	210	570	277	400
		1200	240	620	290	420
		1250	268	672	298	448
Medium		1300	290	720	310	470
	*	1350	314	775	319	496
		1400	330	820	330	520
		1450	360	877	340	544
Large		1500	380	930	350	570
	*	1550	406	970	360	600
		1600	430	1030	370	610
		1650	450	1080	380	640

Table 8-3: Dimensions for the three height settings of the training aid

	a (mm)	c (mm)	d (mm)	g (mm)
Small	210	570	280	400
Medium	310	770	320	500
Large	410	970	360	600

8.4.2 Preliminary design concepts

The main criteria for the training aid design was to support the gymnast if the skill was performed incorrectly, but to provide no interaction with the skill if it was performed correctly. Through the application of a brain storming session, several initial design concepts evolved. The sketches below are not to scale.

Concept 1:

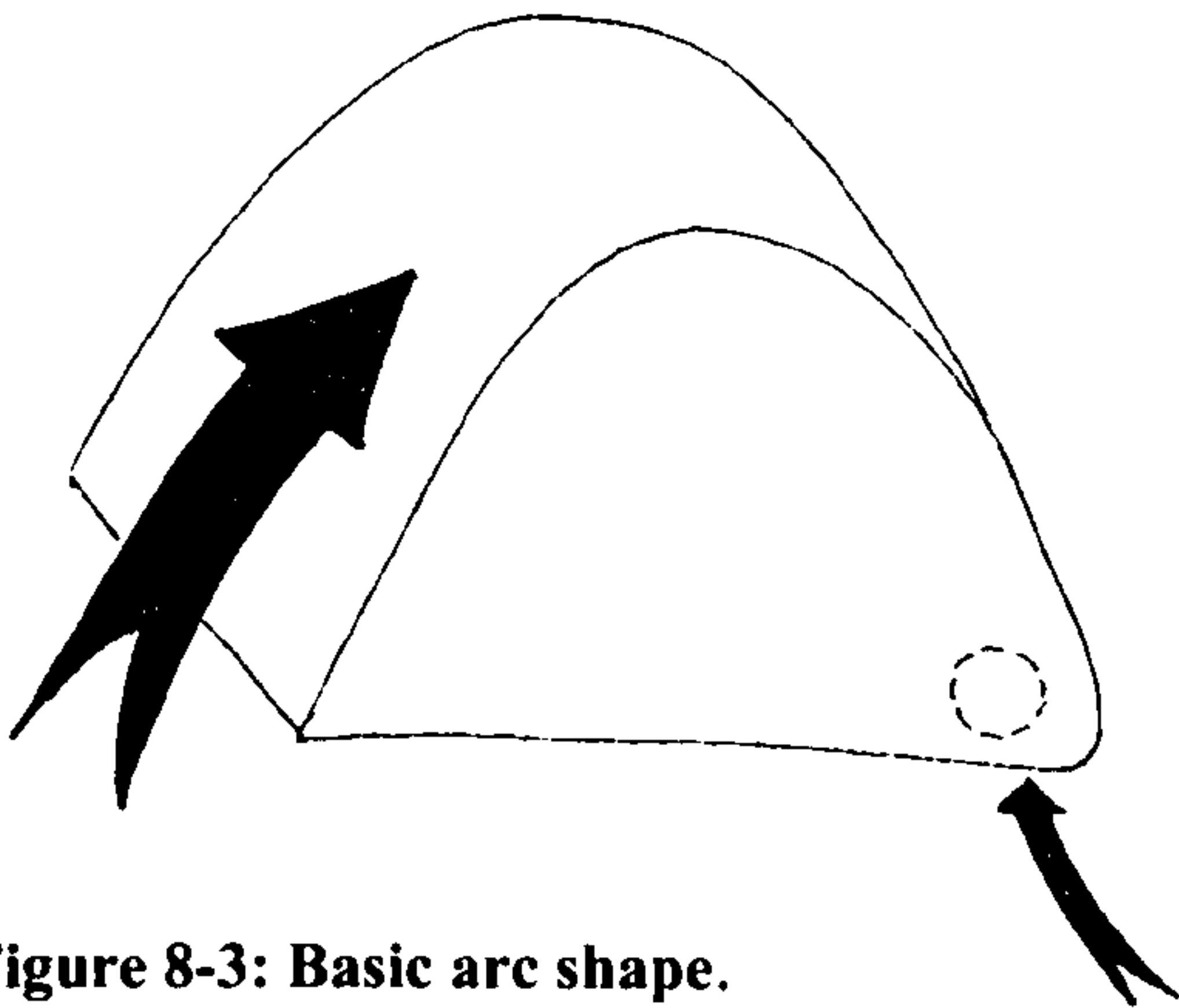


Figure 8-3: Basic arc shape.

This solid foam block is ergonomically shaped to encourage the correct flight path for the gymnast. The gymnast stands to the left of the apparatus and performs the backward handspring over it. It will therefore support the gymnast when necessary. There is an optional weighted section on the bottom right corner to keep the equipment steady.

Concept 2:

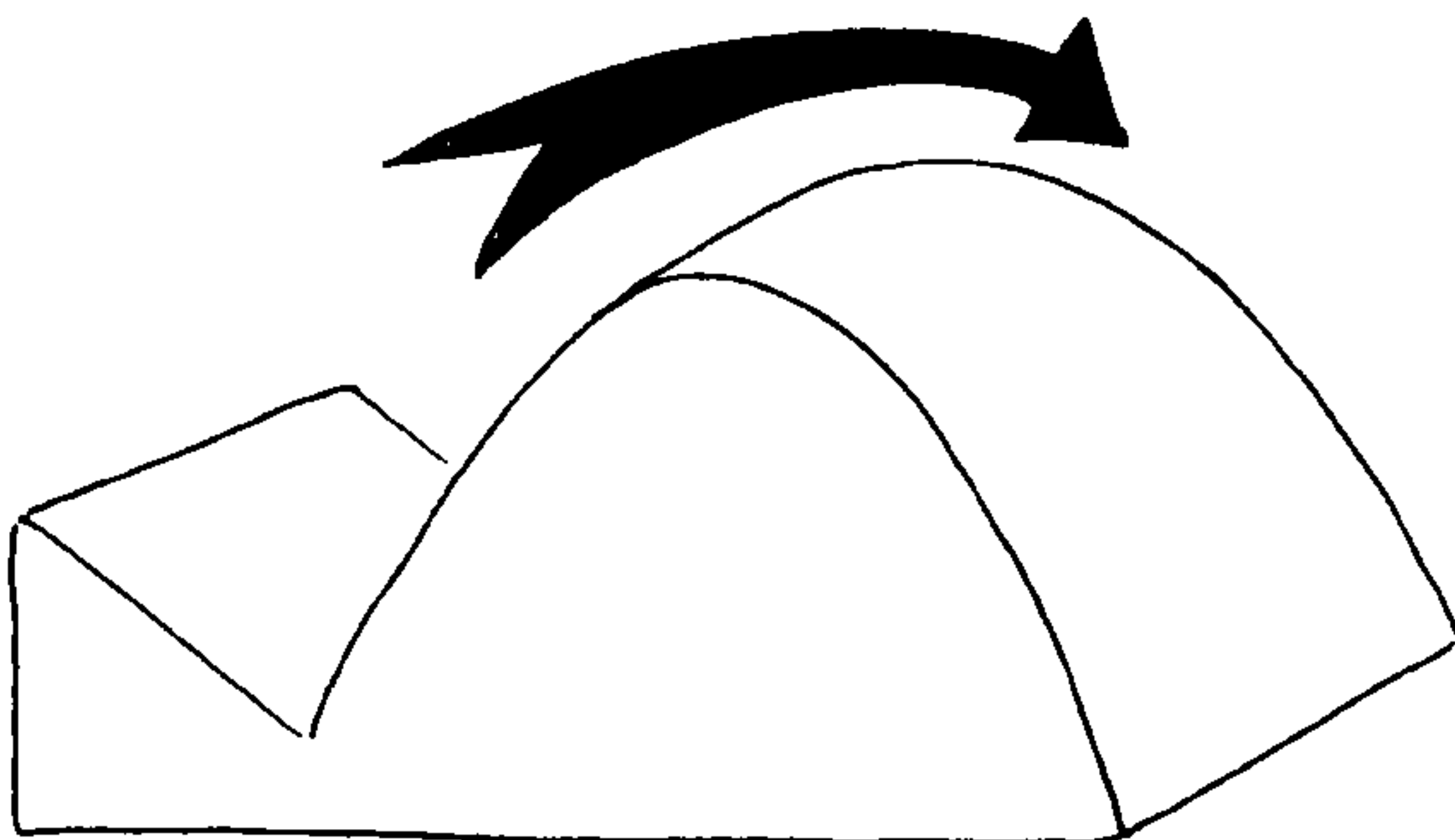


Figure 8-4: Arc with incline.

This concept is an adaptation of concept 1, at the front of the apparatus is an incline to encourage a backward push action.

Concept 3:

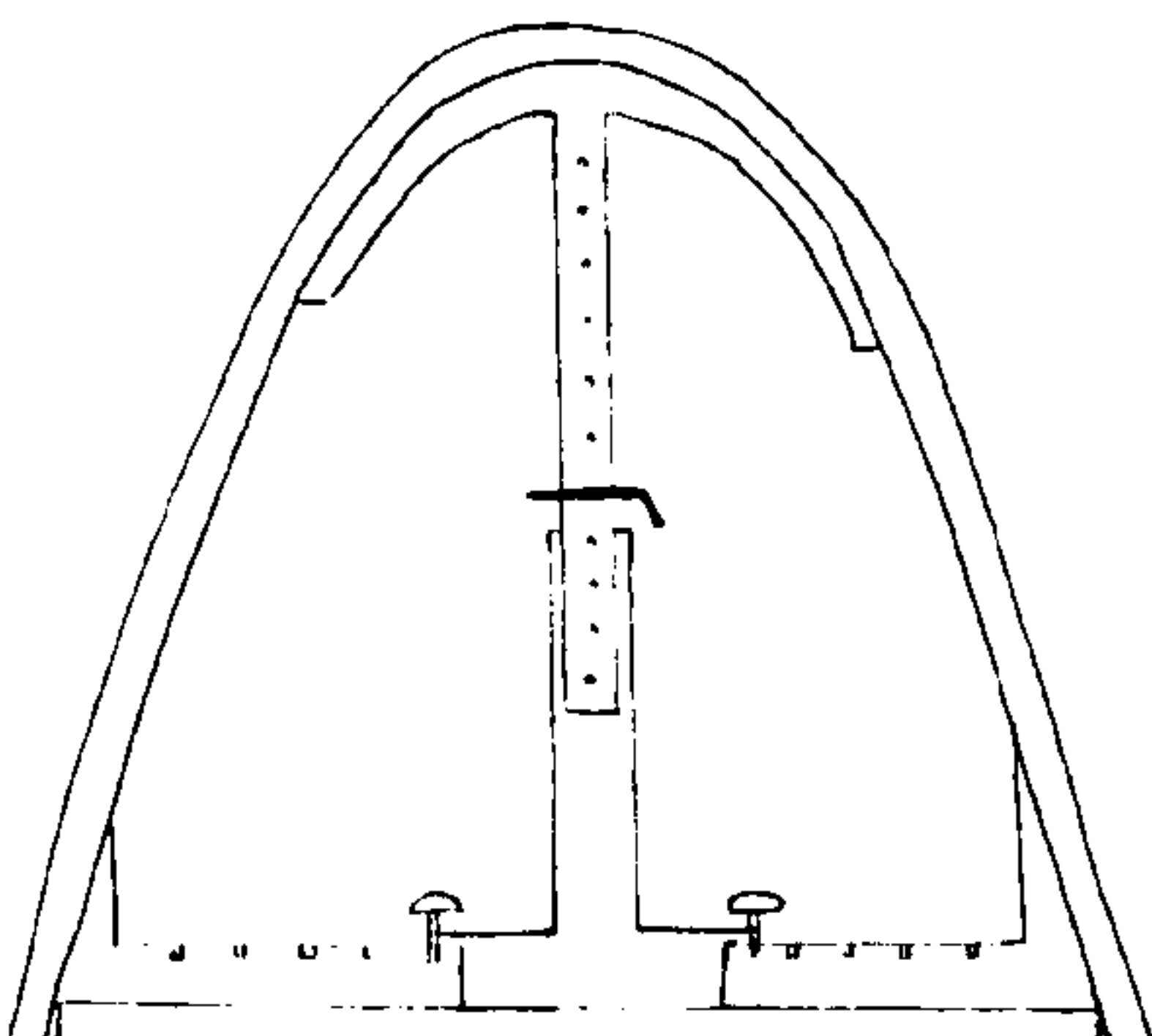
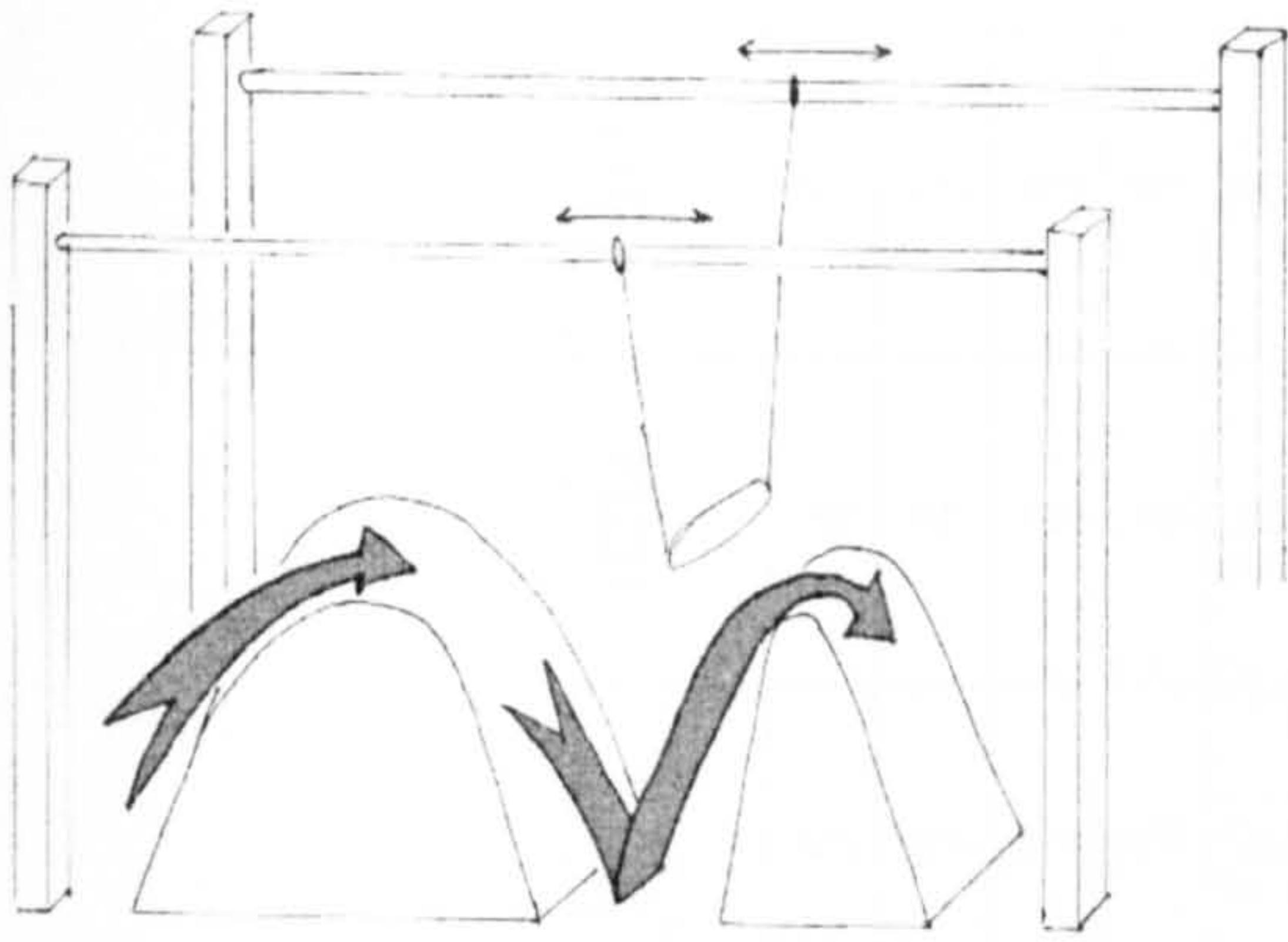
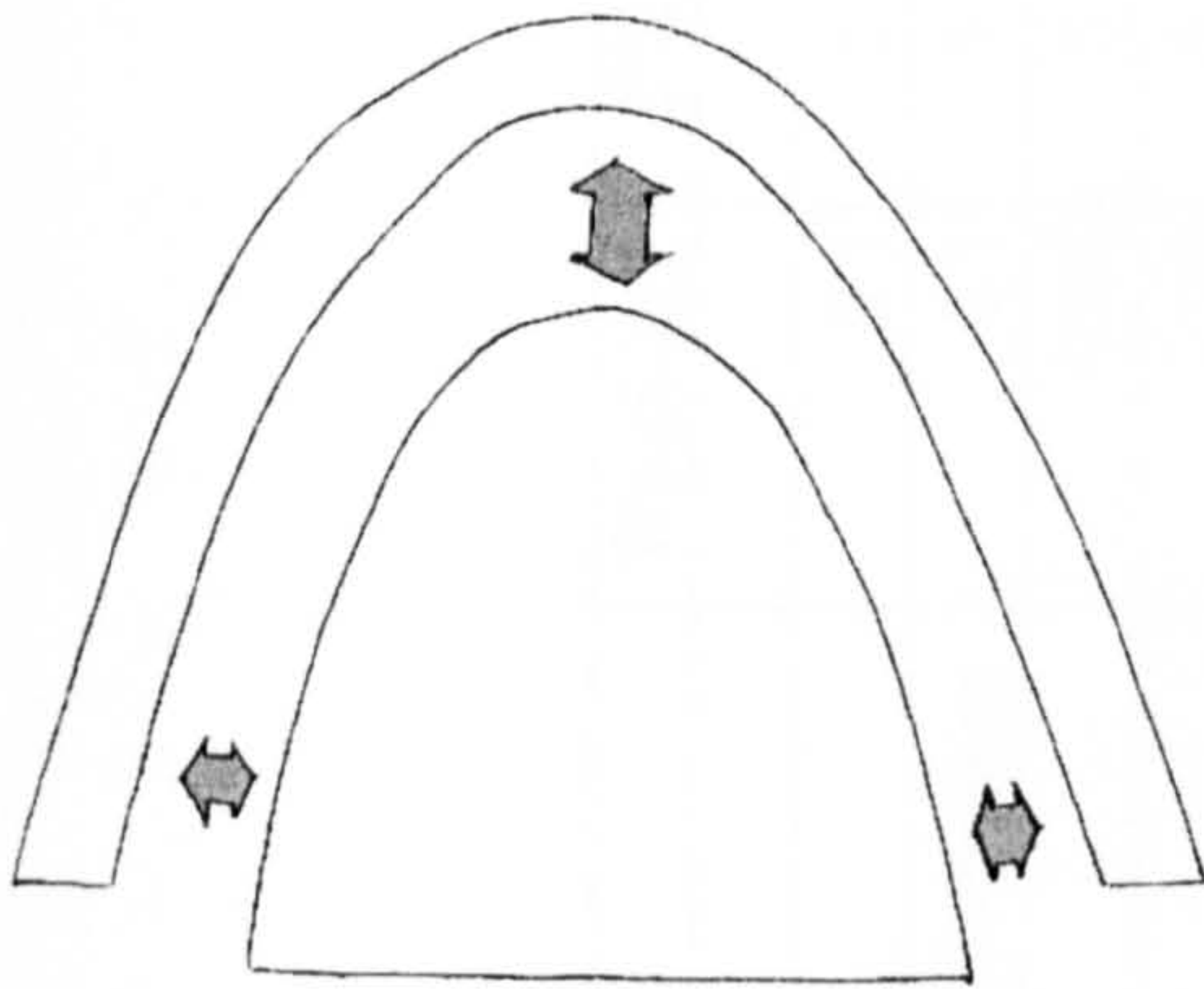


Figure 8-5: Adjustable arc.

Covered in a thick (possibly elastic) foam, this is an adjustable training aid, for both height and length for a variety of gymnasts. The foam layer prevents an impact danger.

Concept 4:**Figure 8-6: Double arc with bungee.**

The harness is suspended on a bungee to reduce the percentage of body weight that the gymnast has to support when landing upside down on the hands. The second block is to encourage the second flight phase and shape.

Concept 5:**Figure 8-7: Velcro adjustable arc**

Concept 5 is a further adaptation of Concept 1, it has additional layers of foam to increase the overall size of the apparatus. These will be held in place by Velcro.

To enable a comparison to be made of these designs, it was necessary to perform a concept analysis. This consisted of comparing each concept to the initial customer criteria detailed in Chapter 3 (Table 3.2). Each concept was graded (1 poor, 5 good) on how well it met the customer requirements, and this was then multiplied by the weighting factor of the customer requirements which was established in the initial requirement trees detailed in Chapter 3 (Figure 3.25). The overall total for each concept was then compared below in Table 8.4:

Table 8-4: Backward handspring training aid design concept analysis

CUSTOMER CRITERIA	Weighting	BH1	BH2	BH3	BH4	BH5
Permits dynamic performance	0.1	5	5	5	4	5
Supports the gymnast but does not interfere with a good performance	0.1	5	5	5	4	5
Alleviates the requirement of support from the coach	0.08	5	5	5	4	5
Should only support first phase of the skill	0.06	5	5	5	0	5
It should be possible to perform a good full skill over the training aid	0.06	5	5	5	4	5
Should pass relevant standards	0.125	5	5	5	5	5
Prevents foreseeable injuries from occurring	0.125	4	4	4	5	4
Must be adjustable for different gymnast sizes	0.09	2	1	4	4	2
Should be possible to use for progression as well as full skill	0.06	3	4	3	3	3
Must be quick and easy to adjust	0.08	0	0	3	2	4
Corrects common mistakes	0.06	2	3	2	2	2
Builds confidence and understanding of the skill	0.08	3	3	3	3	3
1 poor, 5 good	Total	3.8	3.9	4.3	3.7	4.2

From this information, it can be seen that concept 3, an ergonomically-designed adjustable training aid, will best suit customer requirements. It shall therefore be this concept which shall be expanded upon in future design work, taking into consideration the requirement of the *igloo* shape determined in Chapter 7.

8.4.3 Design considerations

From a first observation of the data in Table 8.3, it becomes apparent that the upright section of the training aid will be required to extend from 570mm to 970mm. The upright section is considered to be the most critical part of the training aid as it will provide the most crucial support to the gymnast during a poor performance, and this was the main reason that training aid concept 3 was the highest rating design.

After careful consideration, it was decided that the upright section of the training aid needed to be sufficiently strong to support the gymnast on landing. This section should also be capable of absorbing impact forces so as not to injure the gymnast or make the use of the training aid uncomfortable. Several different options were considered, such as a bungee attached in tension between two columns (Figure 8.6). This would absorb the impact, but was also in danger of causing localised forces through the torso of the gymnast on landing. It also required the two columns to be adjusted in parallel which would generally necessitate two people. Also as the height of the mass centre varies, this would have become a complicated and cumbersome design, with inherent problems.

Solid foam shapes and profiled matting were considered, but were not adjustable, so although soft and easily shaped, would only ever cover one size of equipment which did not meet the design criteria.

It was decided that a solid telescopic section with padding would be the most suitable solution, and would permit more specific shaping to be introduced in the flight path of the first phase of the backward handspring. This would provide the 'adjustable' element of training aid concept 3. The telescopic mechanism was considered for use instead of other height adjustable methods such as winding devices, as it was a standard component in existing gymnastics equipment, as well as being very quick and easy to use. Having a rigid but adjustable column over which the gymnast must perform, encouraged shaping of the first phase of the skill and in turn would also give the maximum support.

8.4.4 Considering the free volume

With the decision made that a metal frame should be used as the basic structure of the training aid, it was crucial that the structure must stay within the free volume of the ‘igloo’ underneath the first phase of the backward handspring. To make the training aid safe, the metal structure was to be covered by shaped foam and matting (as described in concept 3), all of which must also stay within the free *igloo* shape. To achieve this, the free volumes of the three sizes of training aid were mapped out on millimetre squared paper, to permit conceptual designs to be drawn to scale. Basic shapes were evaluated, and modified, and the first design was produced from two rectangular adjacent blocks (Figure 8.8).

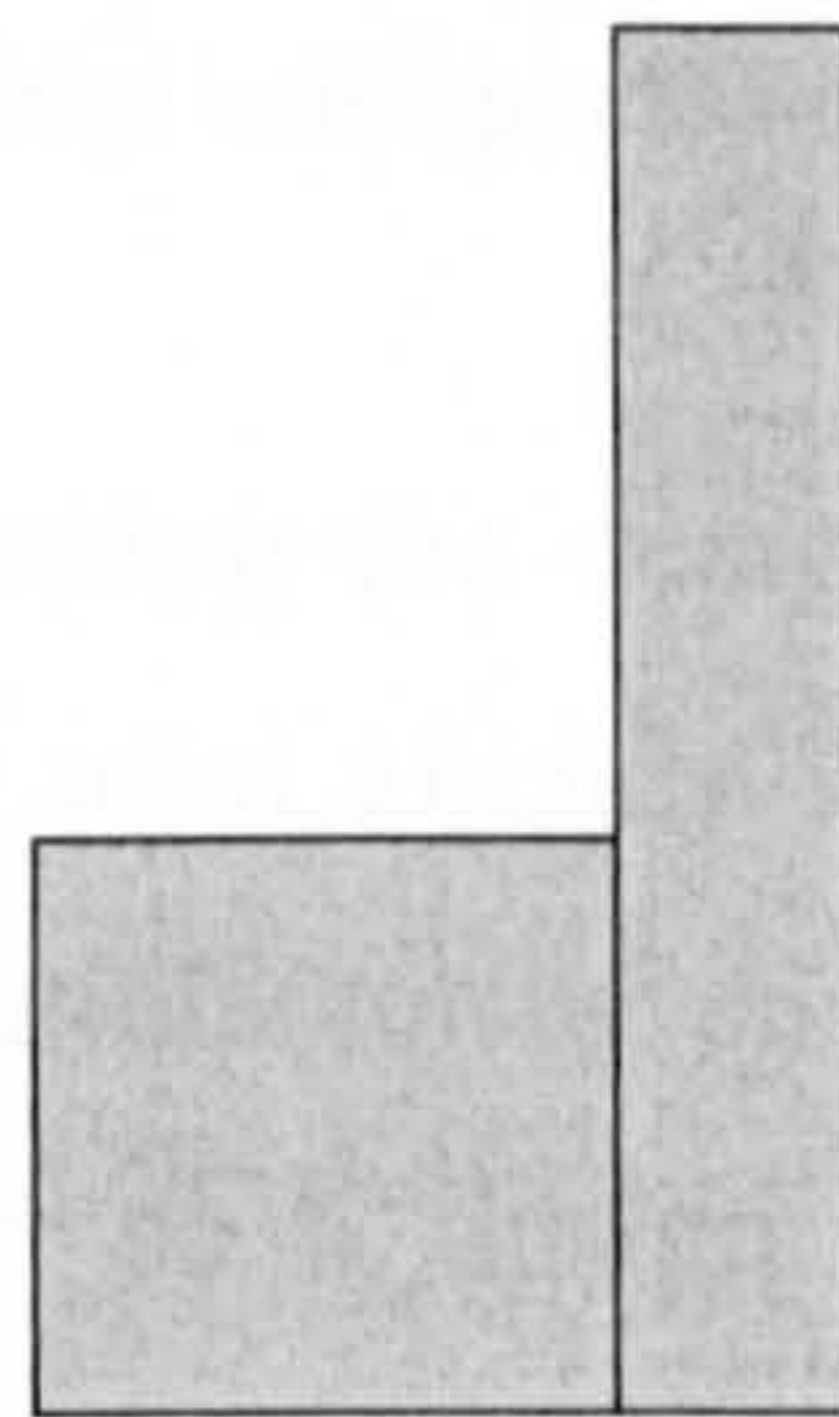


Figure 8-8: Initial design concept – ergonomically designed, adjustable *igloo* shape.

Adjustment of the height and sitting position now had to be considered. It had already been decided that the upright section would be a metal column, and if adjustable in height would be a telescopic section. The height and depth of the seat section now also needed to be determined. Further telescopic sections were considered to modify the height and depth of the seat, but this led to complicated covering and padding of the seat and began to make the training aid too complicated to set up. It was decided that a single basic setting for the training aid, upon which a foam section could be added to alter the shape and size of the training aid would be most customer friendly, and most time effective for changing between gymnasts. It was however essential that it was very clear how to use and attach the additional sections to avoid any customer confusion.

The basic setting of the training aid was to be the smallest size, and sections could be added into it to enlarge the size of the training aid. This prevented the requirement of small gymnasts from starting the performance of the skill already raised above floor level as would have been the case if the large or medium size training aid were chosen to be the basic setting.

The height adjusting telescopic mechanism was to be housed inside the upright section of the training aid. When the height of the training aid was adjusted it became apparent that the metal telescopic section may become uncovered, and so padding was also needed to be added to the back of the training aid for protection (Figure 8.9).

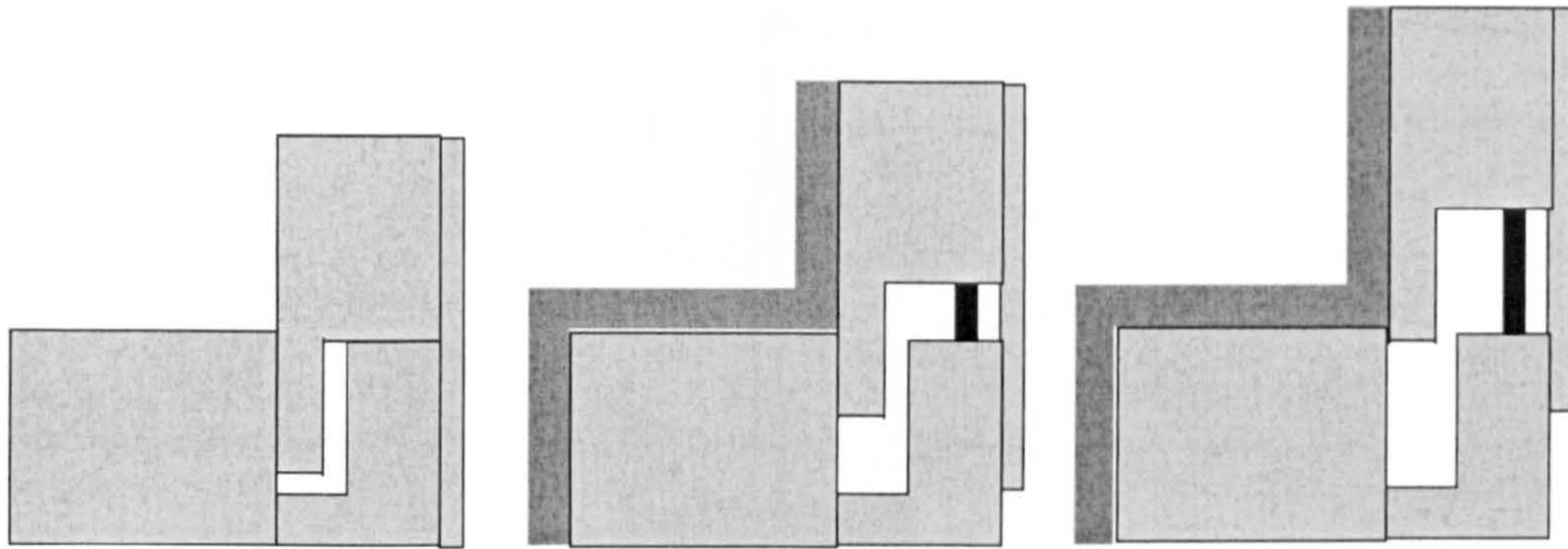


Figure 8-9: Initial concepts for size adjustment.

Any of the materials used during the design of this training aid were as far as possible to be standard components used already in existing gymnastics equipment. A gymnastics equipment design and manufacturing company, Gymnova, had agreed to build the first prototype training aid, and so a design which used the company's standard components was important for the efficient and cost effective production of the prototype.

Before standard components could be used in the design, it was crucial that their suitability be established. If the telescopic section was to be made from standard box section, then the strength of this component must be calculated to ensure the safety of the design.

As a first approximation, the telescopic section was modelled as a single component, fixed to the ground. As not all of the dimensions of the column (telescopic section) were known at this time, as a first approximation it was assumed that the smallest box section of known dimensions 40mm x 40mm (2mm thick stainless steel) would be used for the complete length of the column. There were three possible ways in which the gymnast could create a force on the upright column:

1. *Land directly on top of the column.*
2. *Drive back perpendicular in to the column.*
3. *Hit the column at some angle between vertical and horizontal.*

Assuming the worst case scenario, the full force of the impact would occur at the top of the upright column acting either vertically downward, or horizontally perpendicular to the top of the column. It was assumed that the gymnast had a body mass of 70kg, and

that the gymnast impacted with the training aid at approximately one body weight, the force acting was assumed to be around 700N.

Calculating the Stress in the Column for a Vertical Top Impact (Figure 8.10)

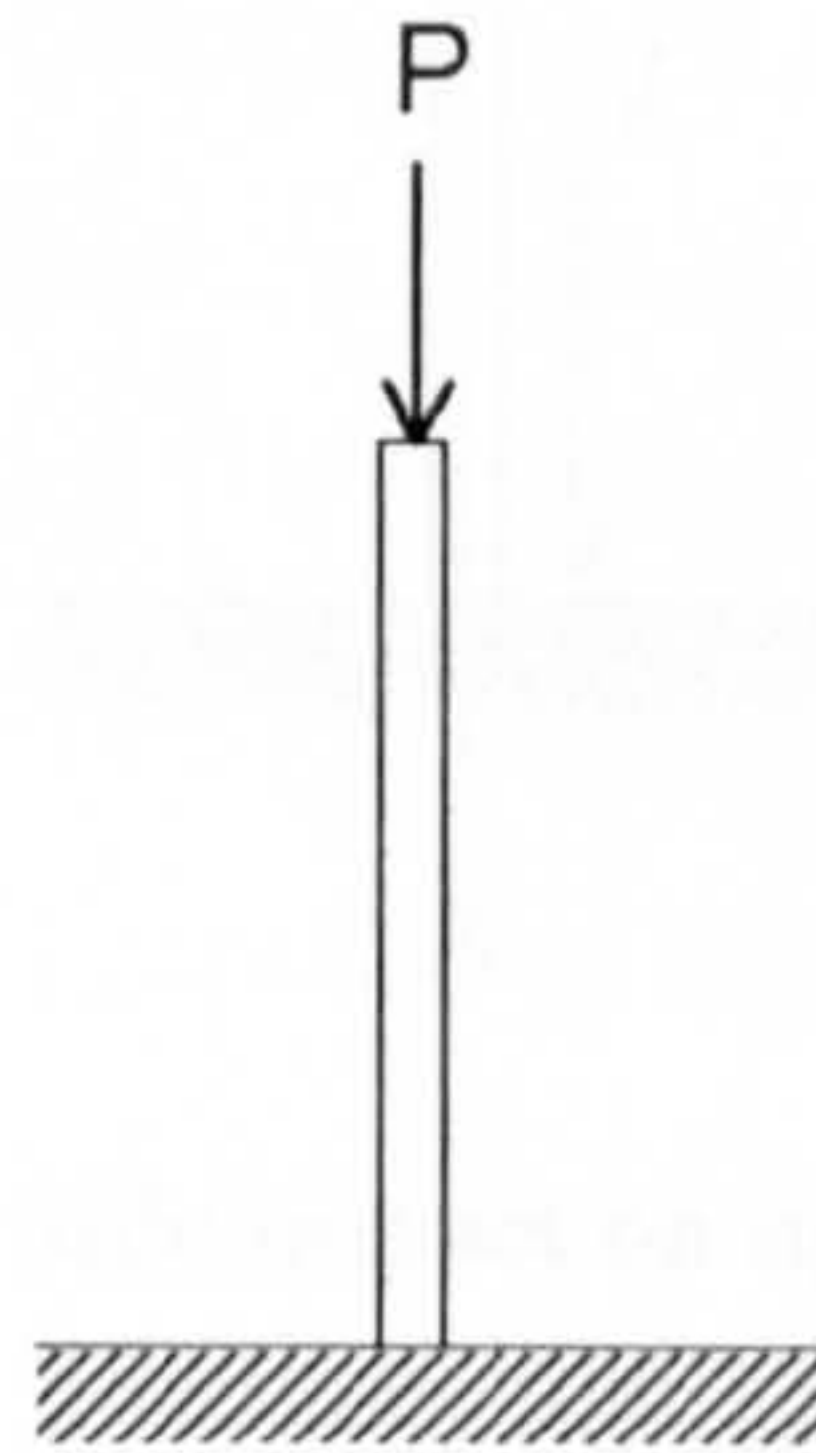


Figure 8-10: Top impact on upright column.

$$\begin{aligned} \text{Area of impact, } A &= 40\text{mm}^2 - 36\text{mm}^2 \\ &= 3.04 \times 10^{-4} \text{m}^2 \end{aligned}$$

For a force, $P = 700\text{N}$

$$\sigma = \frac{P}{A} = \frac{700}{3.04 \times 10^{-4}} = 2.25 \text{MPa}, \text{ (Matthews, 2004).}$$

With a vertical top impact, this scenario may also lead to the column buckling. The critical load at which the column will buckle can be calculated using a standard formula:

Calculating the Critical Buckling Load

$P_c = \frac{\pi^2 EI}{4L^2}$ (Hibbler, 2004) where P_c is the critical load for buckling, L is the length of the section, E is the Young's modulus (196GN/m^2) of the material, and I is the second moment of area (Benham et.al, 1999):

$$P_c = \frac{\pi^2 \times 196 \times 10^9 \times 7.33 \times 10^{-8}}{4 \times 970 \times 10^{-3}} = 36.55 \text{ kN}, \text{ which is two hundred times the magnitude of the expected applied force.}$$

Calculating the Bending Moment of the Column (Figure 8.11)

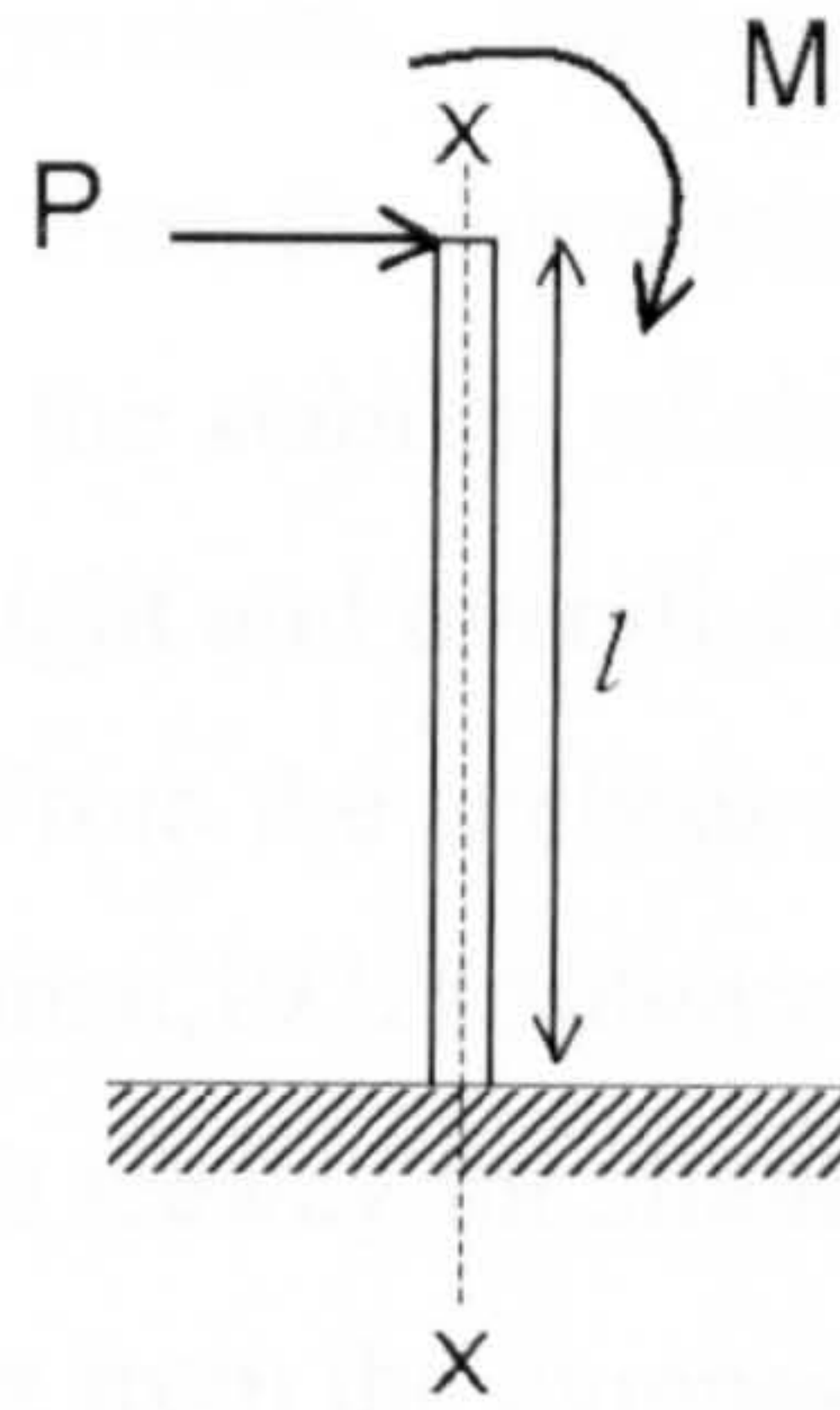


Figure 8-11: Side impact on upright column.

$\sigma = \frac{Mc}{I}$, where M is the bending moment, c is the perpendicular distance from the neutral axis $x-x$ and I is the second moment of area, (Benham, Crawford and Armstrong, 1999).

$$M = 700 \times 970 \times 10^{-3} = 679 Nm$$

$$I = \frac{1}{12} bh^3 = \frac{1}{12} [(40 \times 10^{-3})^4 - (36 \times 10^{-3})^4] = 7.33 \times 10^{-8} m^4 \text{ (2.d.p)}$$

$$c = 40 \times 10^{-3} \times 0.5 = 20 \times 10^{-3} mm$$

$$\sigma = (679 \times 20 \times 10^{-3}) \div 7.33 \times 10^{-8} = 181.56 MPa$$

As general purpose stainless steel has an Ultimate tensile strength (UTS) of 621MPa in compression and tension (Matthews, 2004), the material will not fail during either of these impacts. With the material and dimensions of the column certified as being safe within the approximations made, the design could now be considered in greater detail.

8.5 Detailed design

First to be designed was the metal frame. This would provide the strength of the design. Foam would be then designed to overlay the metal frame, and this would provide the shaping and padding.

8.5.1 The metal structure

It was important that none of the metal frame should encroach into the area used by the backward handspring, and should remain within the igloo free volume. The structure must also be stable for the full range of adjustable heights, be capable of resisting impact

forces, also be light enough to be moved about the gymnasium, and must be easily adjustable by both coaches and gymnasts. The structure was designed using standard stainless steel box section available from the company Gymnova.

The first consideration was the stability of the equipment. The front of the metal frame was narrow to reduce the weight and overall size of the training aid, and the back of the frame was wider for stability. From the analysis of gymnasts' hip and shoulder widths and from reviewed literature (Krogman,1972) 500mm was considered wide enough to fully support both the hips and torso with leeway for slight deviation, but also remained narrow enough to permit both an arm swing from the gymnast and for a coach to get close enough to fully support the gymnast. The front section of the frame also had design considerations such as rigidity, and so cross braces were added into the design of the base. Though incorrect technique, it was appreciated that some gymnasts, while learning may have a wide arm span, and so this dimension after anthropometric considerations was selected as 1000mm at the back of the frame to provide space for this eventuality (Figure 8.12).

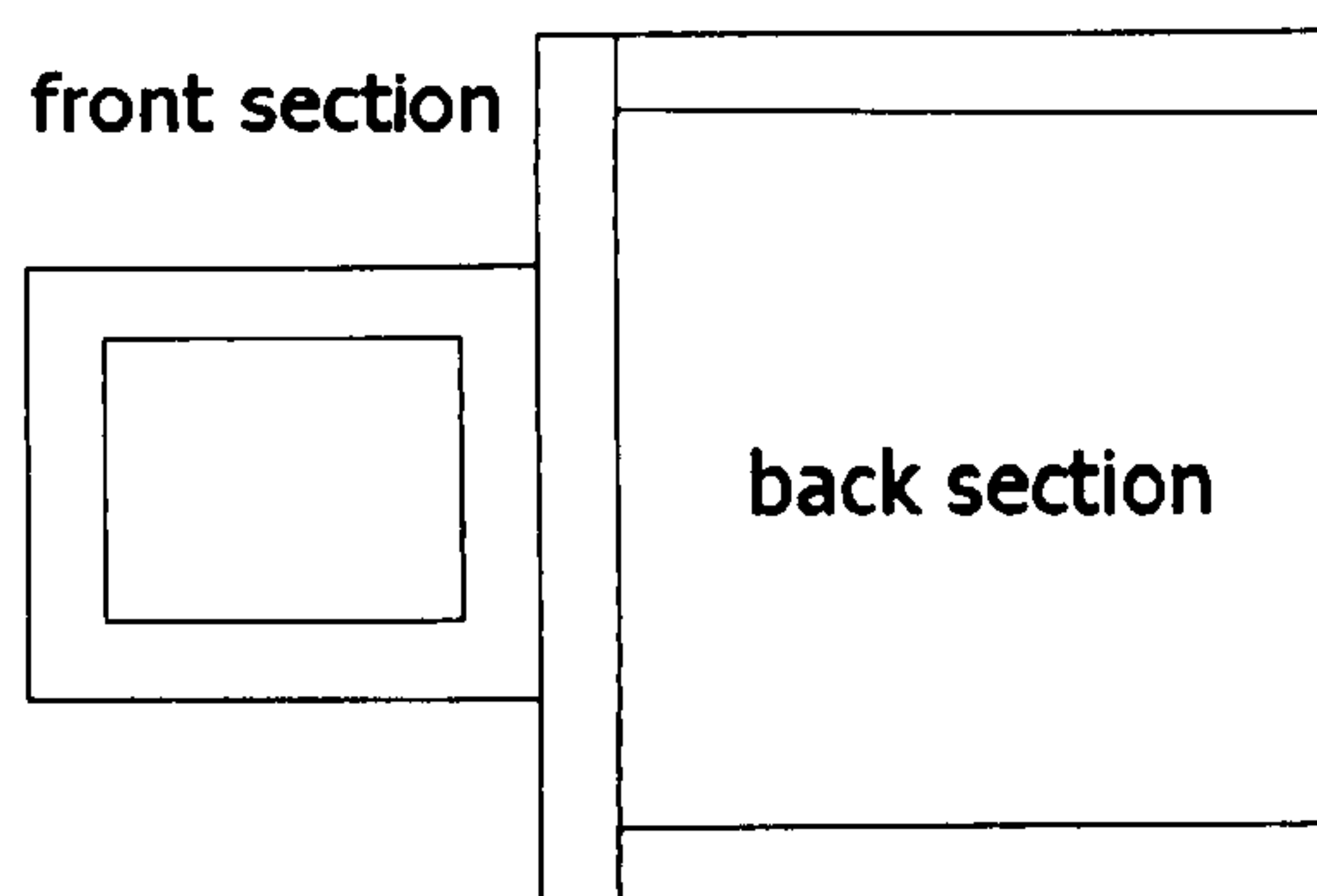


Figure 8-12: Base frame layout.

With the base frame now planned, the location of the upright column needed to be decided. As with this design stability and strength were the main concerns, with the back of the frame positioned wider than the front section, it was decided to model the frame as a triangle. In a triangle, as the centre of mass of the shape is one third up from the base, the column needs to therefore be positioned at least one third of the overall length of the training aid away from the back of the frame. The column should be positioned as far forward as is achievable with the design constraints, in order to make the structure as stable as possible. In doing so the new mass centre of the complete frame will then be positioned in front of the mass centre of base of the frame

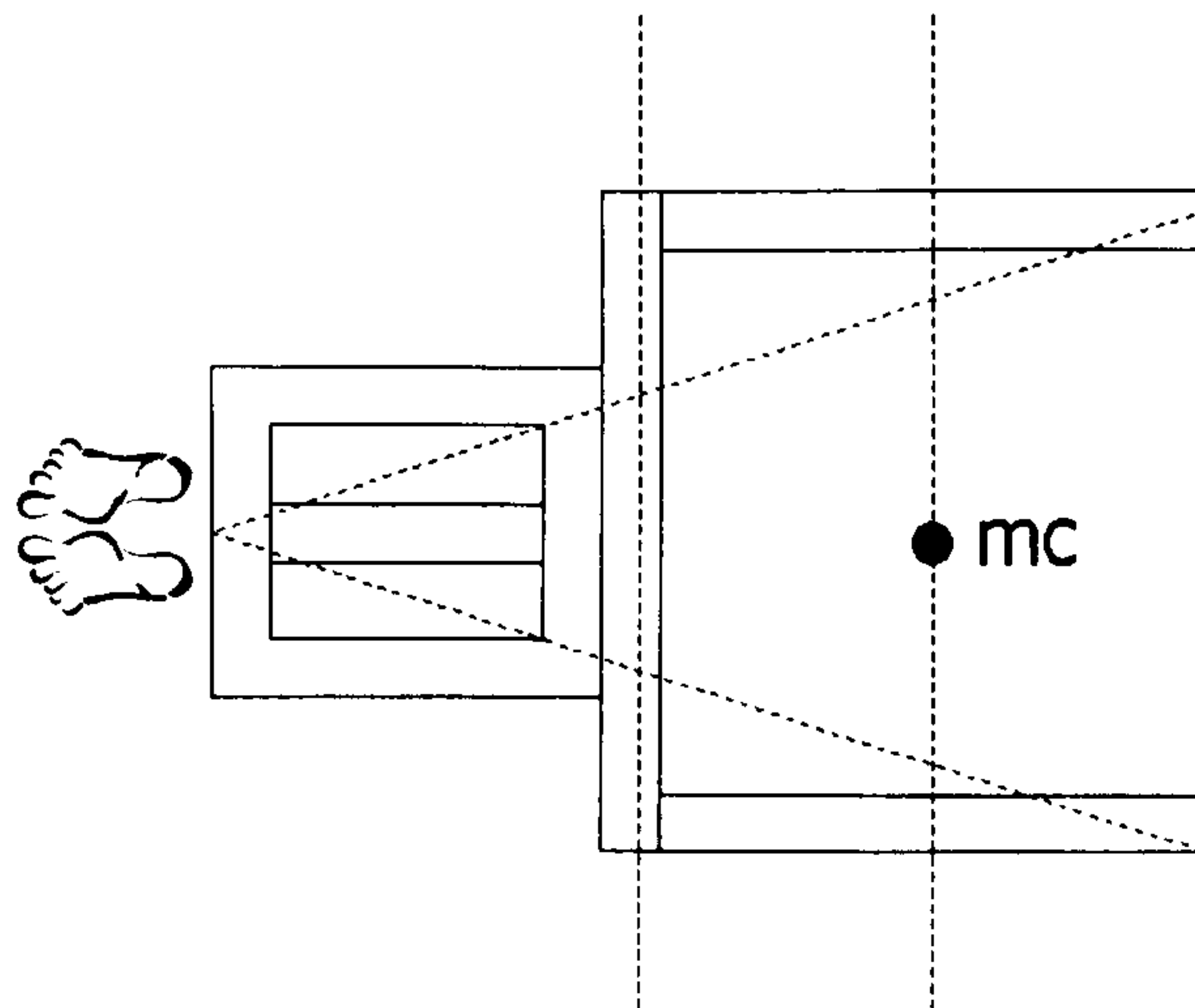


Figure 8-13: Justification for position of telescopic section.

When considering moments about the top of the column, the closer the length of the back of the frame was to the height of the telescopic section (970mm maximum height), the less likely the frame was to tip, regardless of what weight, if any, was in the front section of the frame.

As a method of reducing high impact forces, it was decided that if the frame was designed to permit small amounts of tip during highly dynamic usage, then as long as the angle of tip was small, and the frame always returned to its neutral position flat on the ground, the gymnast would in fact be less likely to be affected by high impact forces.

With this in mind, the telescopic section was positioned in front of the structure's mass centre, but with the length of the back of the frame being a shorter length than 970mm. Two cross braces were added to the design between the base frame and the telescopic section to strengthen the joint for impacts at maximum height (Figure 8.12). Gymnova standard rubber feet were also added to the design to prevent slip and skidding during use. The stability, strength and tipping liability of the training aid were to be tested practically with the manufactured prototype.

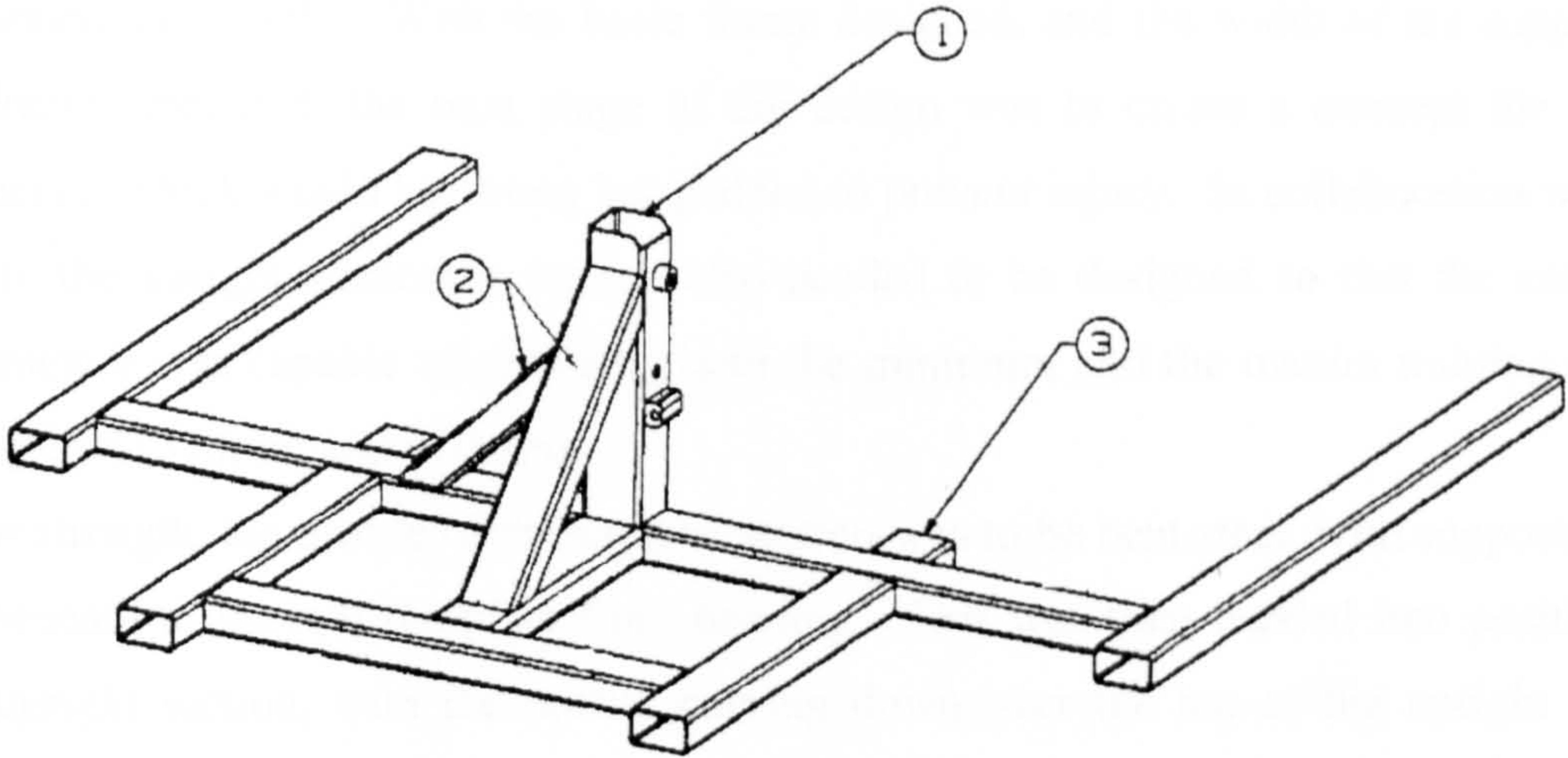


Figure 8-14: Design of the metal frame.

In Figure 8.14 the numbered segment 1 is the bottom stage of the telescopic section, 2 is the two cross braces, and 3 is the main floor level structure.

The two locking devices on the telescopic section which controlled the height settings (Figure 8.15) were placed at the side of the frame to prevent any chance of the gymnast hitting them during a performance. This also produced easier access for customer adjustment.



Figure 8-15: Height locking mechanics.

It was decided that the width dimension should stay constant throughout the entire front section of the training aid from the metal structure on the floor to the width of the padding on top of the telescopic section. This was to ensure that the gymnast could, if required, swing the arms during takeoff as mentioned previously, but also to provide enough width to fully support the torso when landing on the top of the training aid.

8.5.2 The support section and upright column

The support section was the uppermost section of the training aid. It was to be attached to the top of the telescopic section, and was to support the gymnast when the skill

was performed incorrectly. With the basic frame designed, and the width of the support section already specified, the next stage of the design was to create a concept for the support section which would be strong but padded to prevent injury. In collaboration with this design, the upright telescopic section also needed to be designed so that the entire upright structure was capable of obtaining both the minimum and the maximum training aid heights required (570mm and 970mm).

For strength, the profile of the support section was to be bent steel, with supporting brackets beneath to prevent the plate from bending. This was then welded into position onto the upright section, with the profile curving down over the top of the upright for added support (Figure 8.16). On top of the metal plate was to be a layer of dense foam to cushion the high impact forces, and on top of that was a further layer of softer foam to improve the gymnast's comfort during use. All of these differing component layers needed to be taken into consideration during the calculations of the complete upright section height.

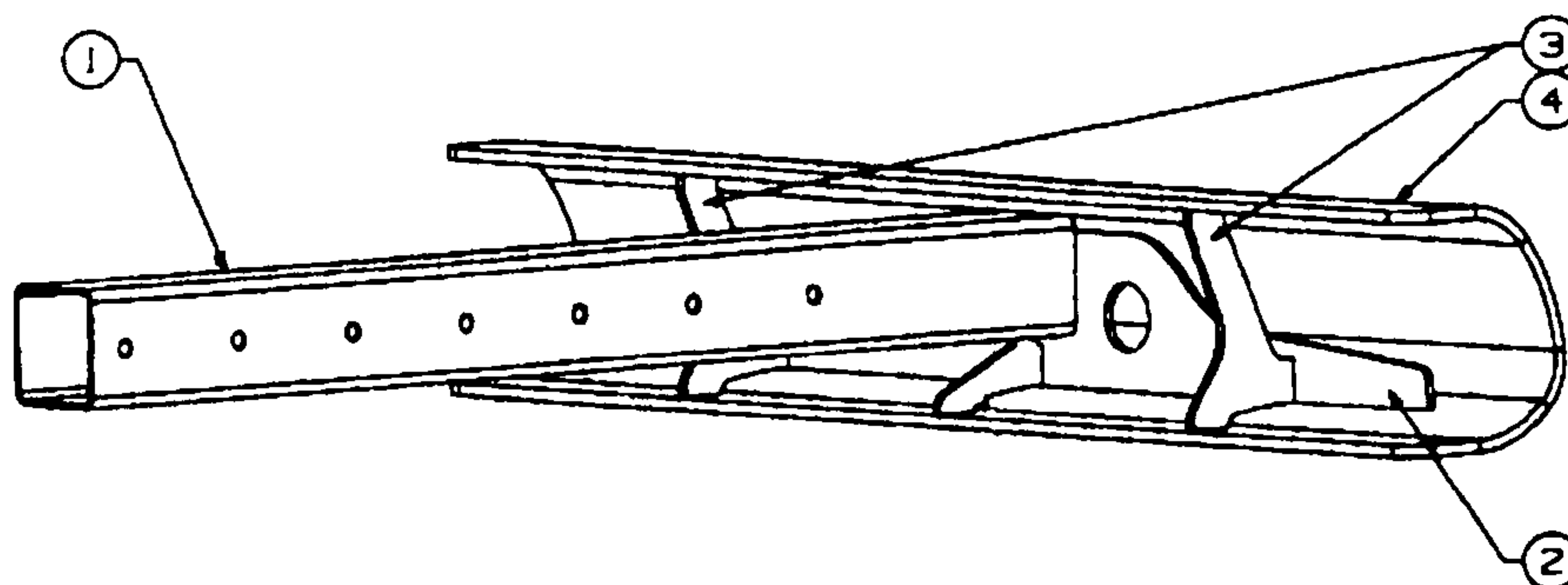


Figure 8-16: Design of the support section.

In Figure 8.16 above, the numbered section 1 is the top stage of the telescopic sections, 2 is the plate to which the telescopic section and the profiled metal plate are attached, 3 is the strengthening brackets, and 4 is the profiled metal plate.

Upright Telescopic Section Calculation

From initial calculations it became obvious that it was impossible to create the range of heights required from just two telescopic sections: a third section was also needed. Specific lengths were known, for example the amount of overlap (125mm) between two adjacent telescopic sections, and the position, size and spacing of the locking mechanisms (185mm from the top on the outer box section, with the pin inserting at 40mm from the top of the box section) were already predetermined by the existing Gymnova components (Figure 8.14).

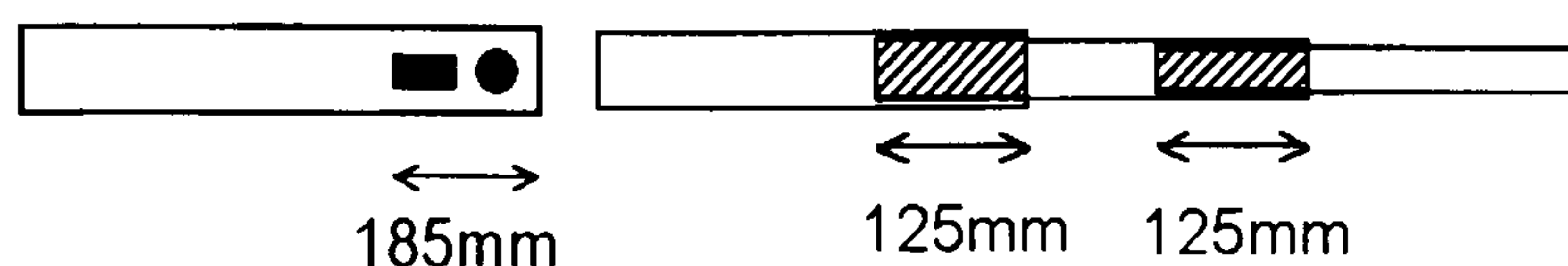


Figure 8-17: Dimensions of existing components.

The support section had for comfort and safety a minimum total depth of 100mm, including a depth for an overhanging mat which was introduced into the design to cover the exposed metal section of the upright column when extended at medium or full height. The rubber feet and bottom of the metal frame also consumed a further 37mm of the available height. This left a height of 833mm to be achieved using three telescopic sections, but also a height of only 433mm when fully collapsed to the minimum height setting, with the locking mechanism still engaged (Figure 8.15).

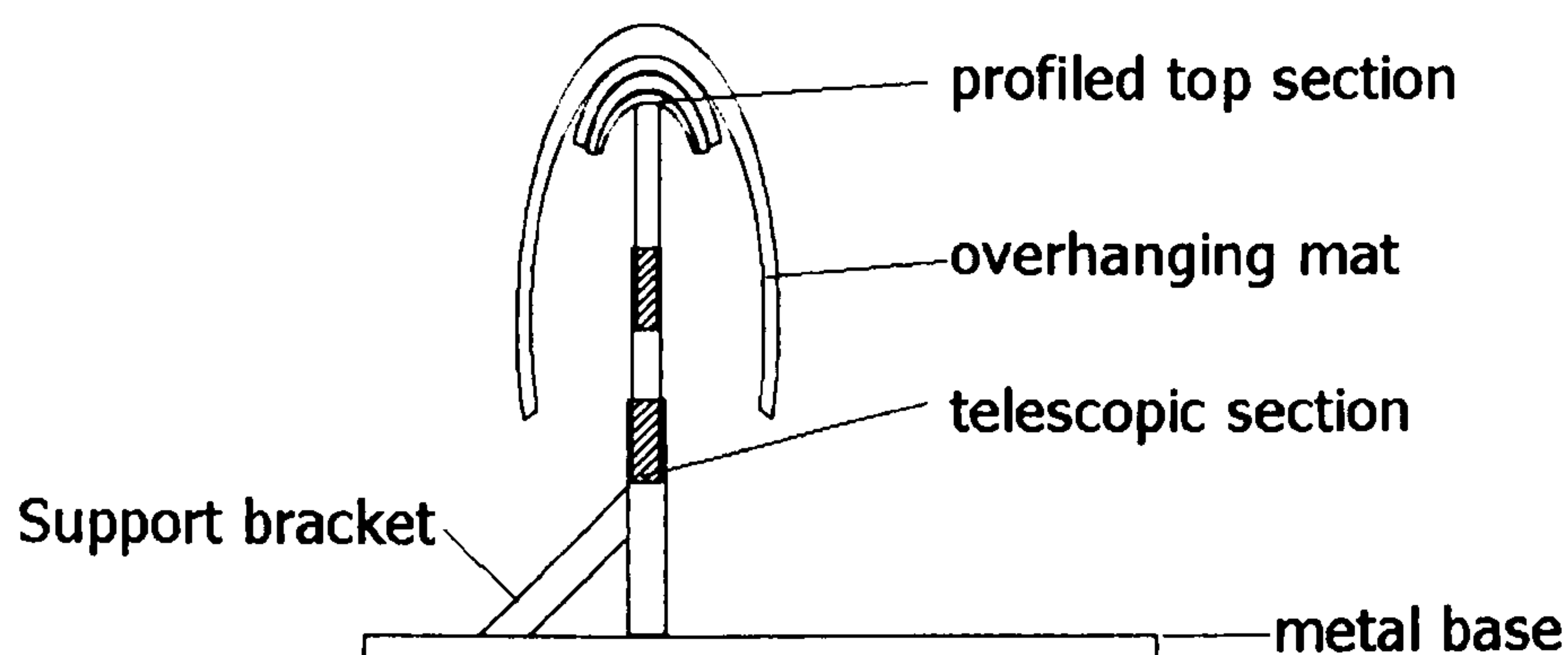


Figure 8-18: Upright section full composition.

Complete upright section design

The minimum collapsible height of the frame work was required to be 433mm. The middle segment of the telescopic section is the same length as the top segment, and the top segment has a 5mm overlap ($428 + 5 = 433$) on which to weld the profiled metal plate, making the middle segment a length of 428mm. Ideally the bottom segment would also be this length except the middle segment had a 185mm long locking device on it, reducing the bottom section to only $728 - 185 = 243$ mm in length. The bottom segment also had a 185mm long locking device attached.

Thus: $243 - 125 + 428 - 125 + 433 = 854$, which is greater than the required 833. Adding now the depth of the top section of foam and, and the 37mm consumed by the rubber feet and base frame: $854 + 100 + 37 = 991$, which is taller than the required 970,

and still collapses down to the required 570mm minimum height of the complete training aid. With the dimensions established, the actual strength of the upright section must be recalculated to a more representative value.

Calculating the Bending Moment of the Telescopic Section

To calculate the bending moment of the three segment telescopic section (Figure 8.19), it has again been assumed that the bottom section is attached to the ground. The applied force is $P = 700\text{N}$ as in the previous calculation, and no support brace is attached.

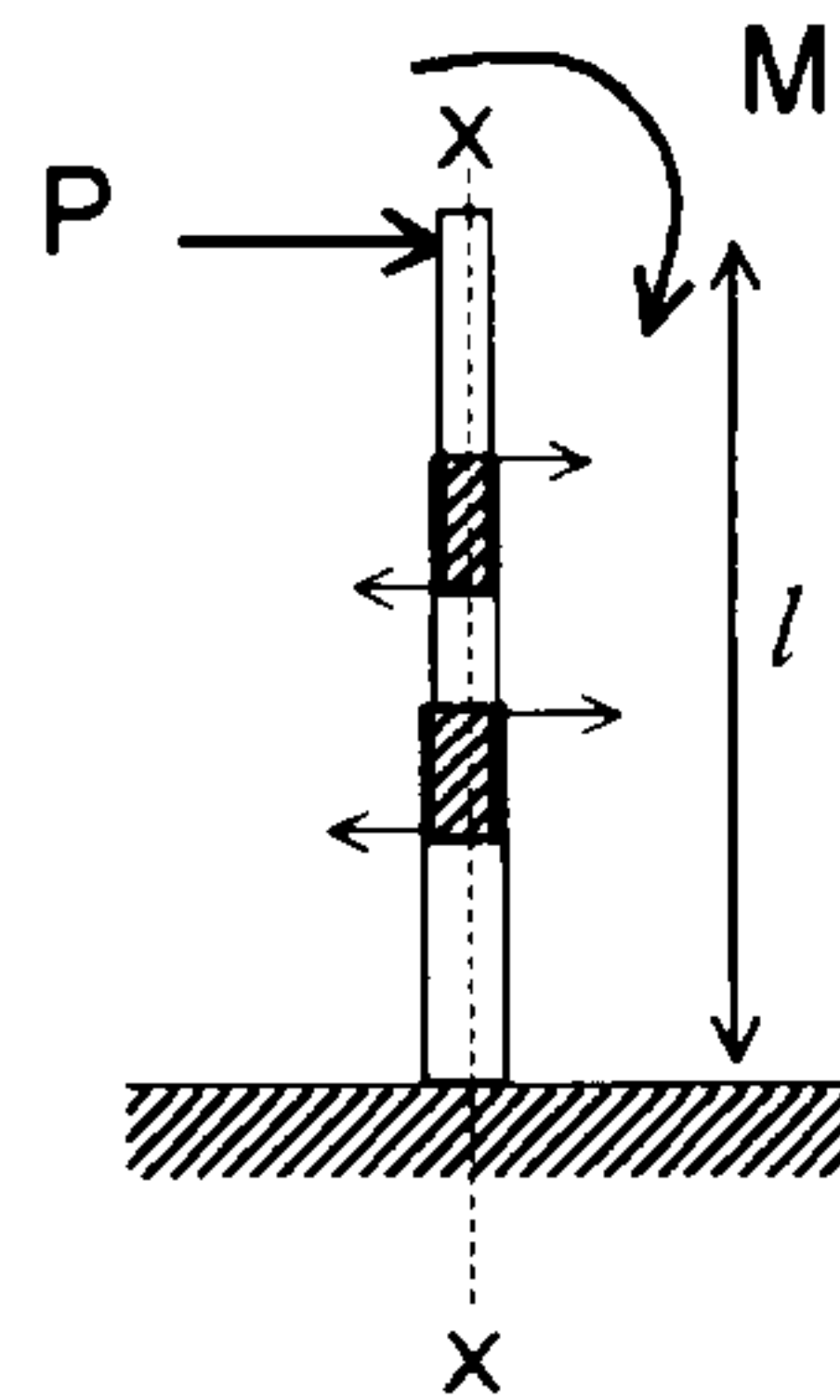


Figure 8-19: Telescopic bending scenario.

Analysis the top segment of the telescope, and balancing moments (Figure 8.17):

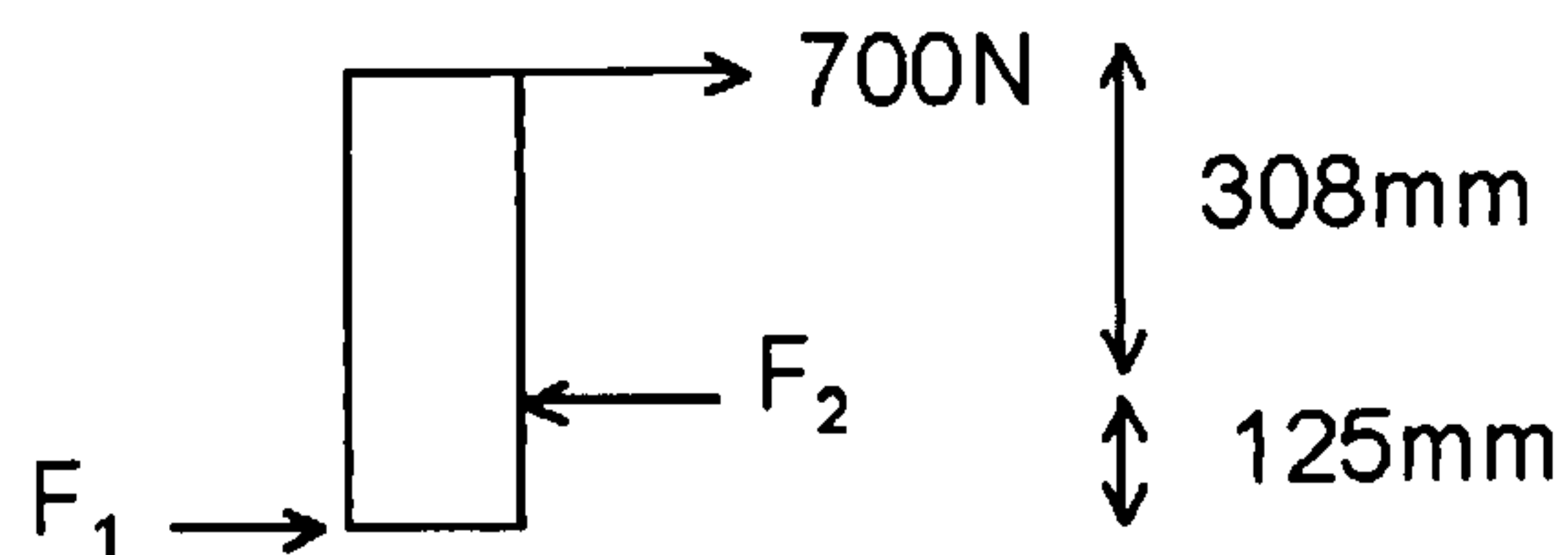


Figure 8-20: Top telescopic section.

$l = 433 - 125 = 308\text{mm}$, and the segment is 2mm thick stainless steel, 40mm square box section.

Taking moments about F_2 :

$$700 \times 308 = F_1 \times 125$$

$$F_1 = 1724.8\text{N}$$

Taking moments about F_1 :

$$F_2 \times 125 = 700 \times 433$$

$$F_2 = 2424.8\text{N}$$

The bending moment for this section will occur where the maximum force is applied at F_2 , at the top of the overlapping section. There will be a shear stress through this segment: $\tau = \frac{Q}{A}$, where Q is the shear load (Matthews, 2004).

$\tau = 2424.8 \div [(40 \times 10^{-3})^2 - (36 \times 10^{-3})^2] = 7.98\text{MPa} < 621\text{MPa}$, the UTS of the material.

Analysis of the middle segment of the telescope, and balancing moments :

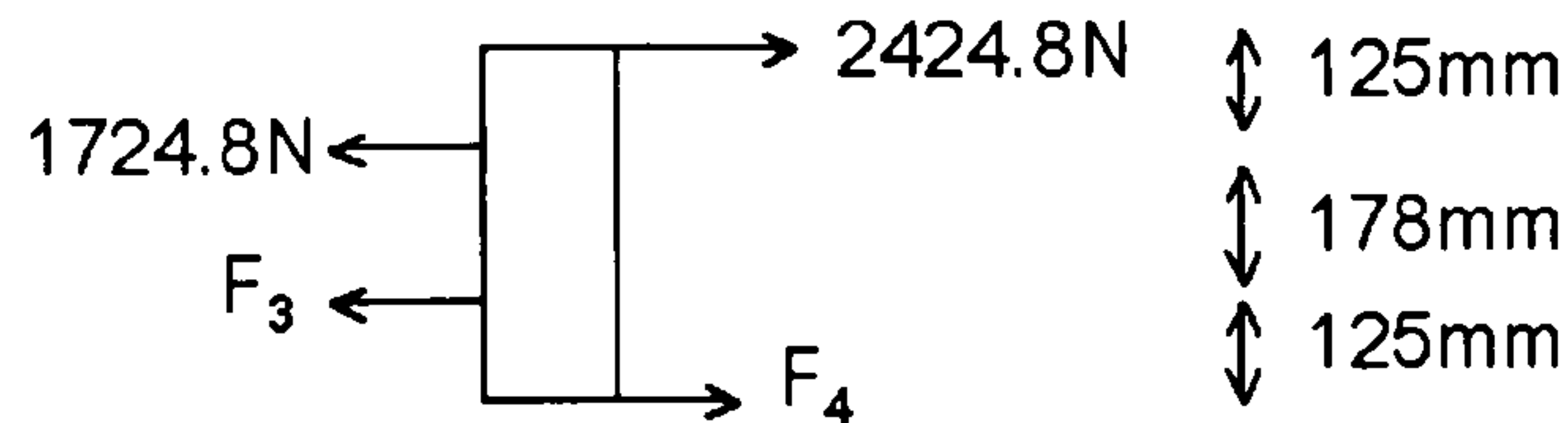


Figure 8-21: Middle telescopic section.

$l = 428 - 125 - 125 = 178\text{mm}$, and the segment is 2mm thick stainless steel, 45mm square box section.

Taking moments about F_4 :

$$F_3 \times 125 + 1724.8 \times 303 = 2424.8 \times 428$$

$$F_3 = 4121.6\text{N}$$

Taking moments about F_3 :

$$F_4 \times 125 + 1724.8 \times 178 = 2424.8 \times 303$$

$$F_4 = 3421.6\text{N}$$

$\tau = \frac{Q}{A} = 4121.6 \div [(45 \times 10^{-3})^2 - (41 \times 10^{-3})^2] = 11.98\text{MPa} < 621\text{MPa}$ the UTS of the material.

Analysis of the middle segment of the telescope, and balancing moments:

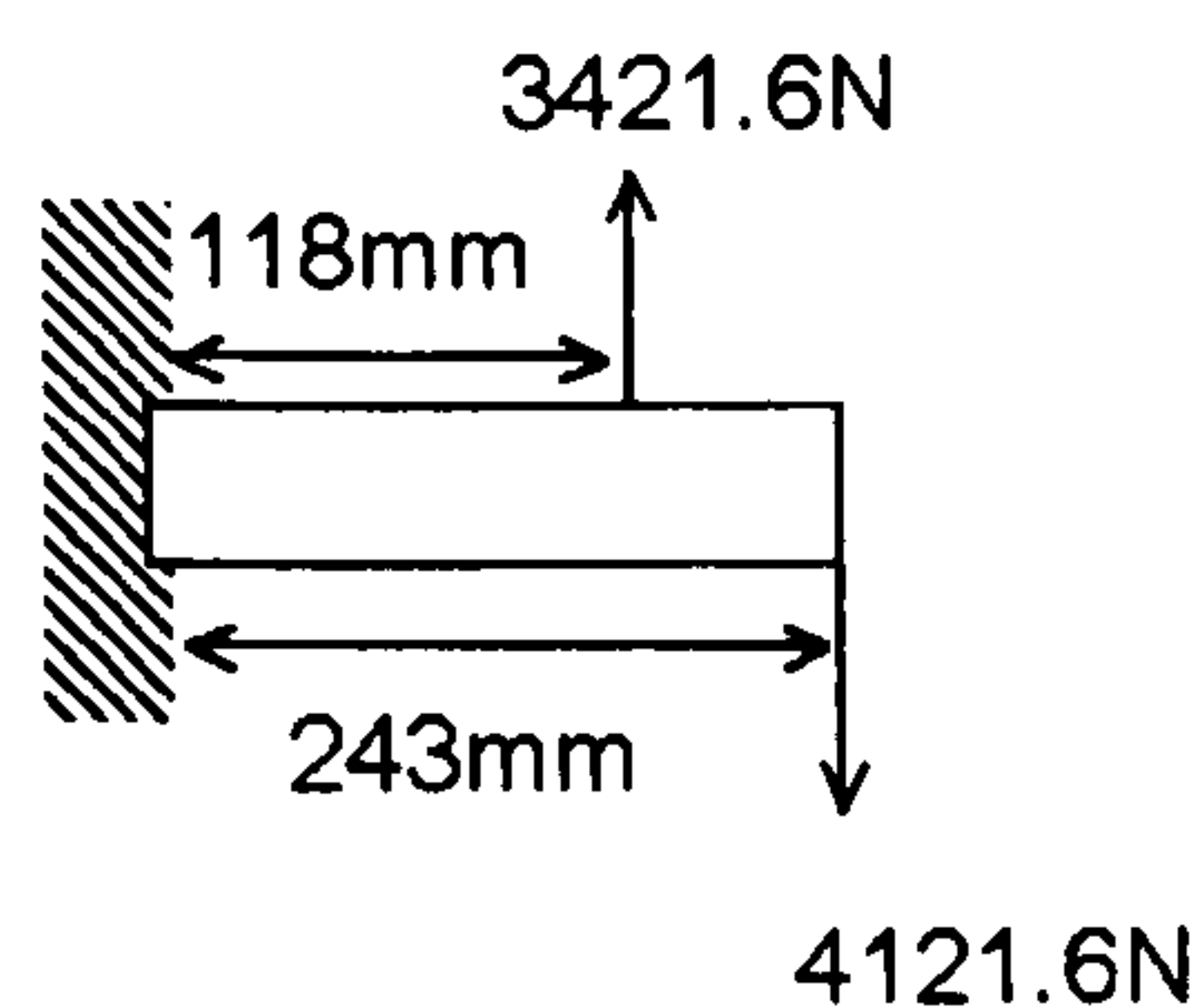


Figure 8-22: Bottom telescopic section.

$l = 243 - 125 = 118\text{mm}$, and the segment is 2mm thick stainless steel, 50mm square box section.

Calculating the bending moment of the section:

$$4121.6 \times 243 \times 10^{-3} - 3421.6 \times 118 \times 10^{-3} = \text{BM}$$

$$\text{BM} = 597.8\text{Nm}$$

Calculating the bending stress:

$$\sigma = \frac{Mc}{I} = (597.8 \times 0.025) \div 1.477 \times 10^{-7} = 101.18\text{MPa} < 621\text{MPa}, \text{ the UTS of the}$$

material. Assuming that the segment is rigid and the applied force is therefore the same at the top of the segment as it is at the bottom:

$$\begin{aligned} \tau &= \frac{Q}{A} = (4121.6 - 3421.6) \div [(50 \times 10^{-3})^2 - (46 \times 10^{-3})^2] \\ &= 700 \div 3.84 \times 10^{-4} = 1.82\text{MPa} \end{aligned}$$

Also if the segment is assumed to be welded into place, the strength of the weld can be calculated and compared to the shear stress. If the weld is assumed to be a perfect weld, with no residual stresses, the permissible shear stress for a butt or fillet weld for stainless steel = $0.30S_{ut}$, where S_{ut} is the UTS of the material (Shigley and Mischke, 2001).

Permissible stress = $0.30S_{ut} = 0.3 \times 621\text{MPa} = 186.3\text{MPa}$, which is more than ten times the calculated shear stress at the weld site.

To combined both the shear and bending stresses to calculate the principal stresses involved in this segment, a Mohr's stress circle calculation must be performed:

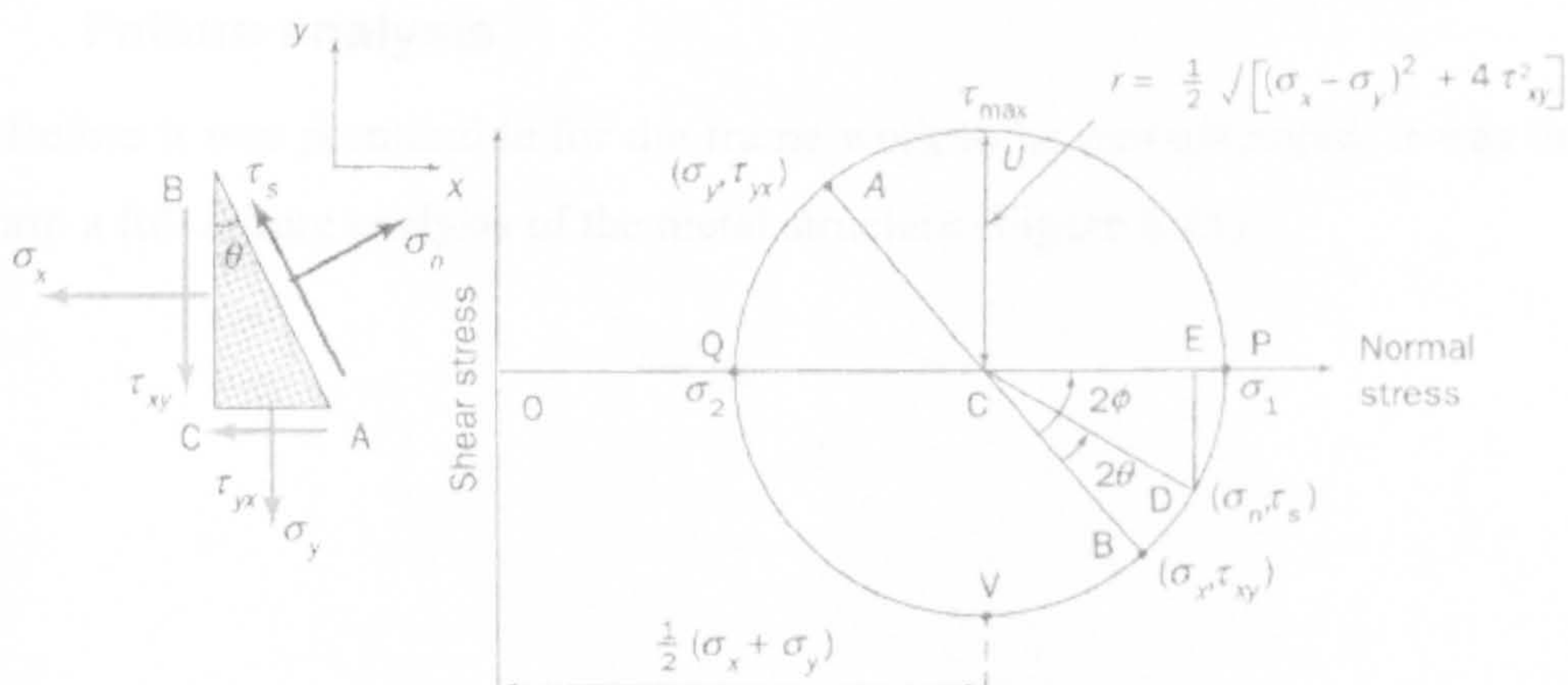


Figure 8-23: Mohr's circle (Benham, 1996, pp 299, fig 11.8).

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \frac{1}{2}\sqrt{[(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2]} \quad \text{and} \quad \sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \frac{1}{2}\sqrt{[(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2]}$$

(Benham et. al, 1999).

Calculating the maximum principal stress, σ_1 :

$$\sigma_1 = \frac{101.18 \times 10^6}{2} + \frac{1}{2}\sqrt{[(101.18 \times 10^6)^2 + 4(1.82 \times 10^6)^2]} = 151.84 \text{ MPa}$$

Under the assumptions of von Mises (Benham et. al, 1999), the maximum principal stress for this scenario must be compared to the Yield Stress of the material, which for general purpose stainless steel is 276MPa (Matthews, 2004). It has therefore been shown that this section of the training aid will not fail under expected loading. With the design also having two supporting brackets attached to the bottom section of the column for further strength and support, it can be expected that the upright column should be suitably durable to impact stresses.

There is one final mode in which the actual steel column could fail: As it has been established that the three telescopic sections will be held in place by pin locking mechanisms, for the situation when the load is directly applied downward onto the column, the likelihood of the pin shearing under the load must also be calculated. Assuming that the telescopic sections are tight fitting, with the diameter of the metal pin being 10mm, the relative stress can be calculated:

$$\sigma = \frac{P}{A} = \frac{700}{\pi(10 \times 10^{-3})^2} = 2.23 \text{ MPa, which is well within the limits of stainless steel.}$$

8.5.3 Failure analysis

Before it was permissible for the frame work to be manufactured, it was important to perform a full failure analysis of the metal structure (Figure 8.25).

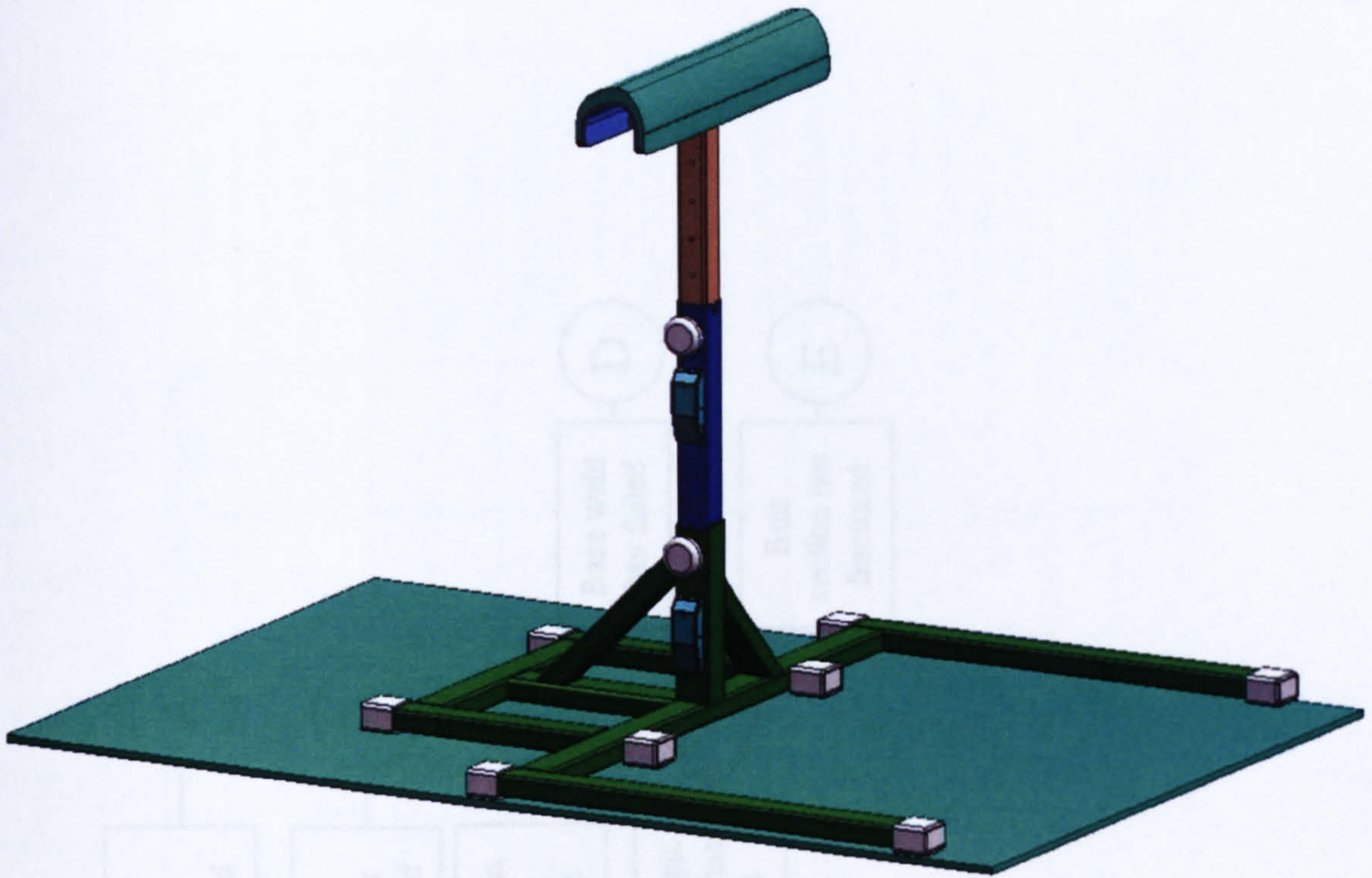


Figure 8-24: The full metal framework.

In order to achieve this a fault tree was produced from the training aid to identify any design weaknesses and to analyse each component on a basic level and how the failure of each component may prevent the training aid from functioning properly (Figure 8.26). The information within the fault tree was then expanded to produce a Failure Modes and Effects Analysis (FMEA) worksheet as in Chapter 5 (Figure 8.27).

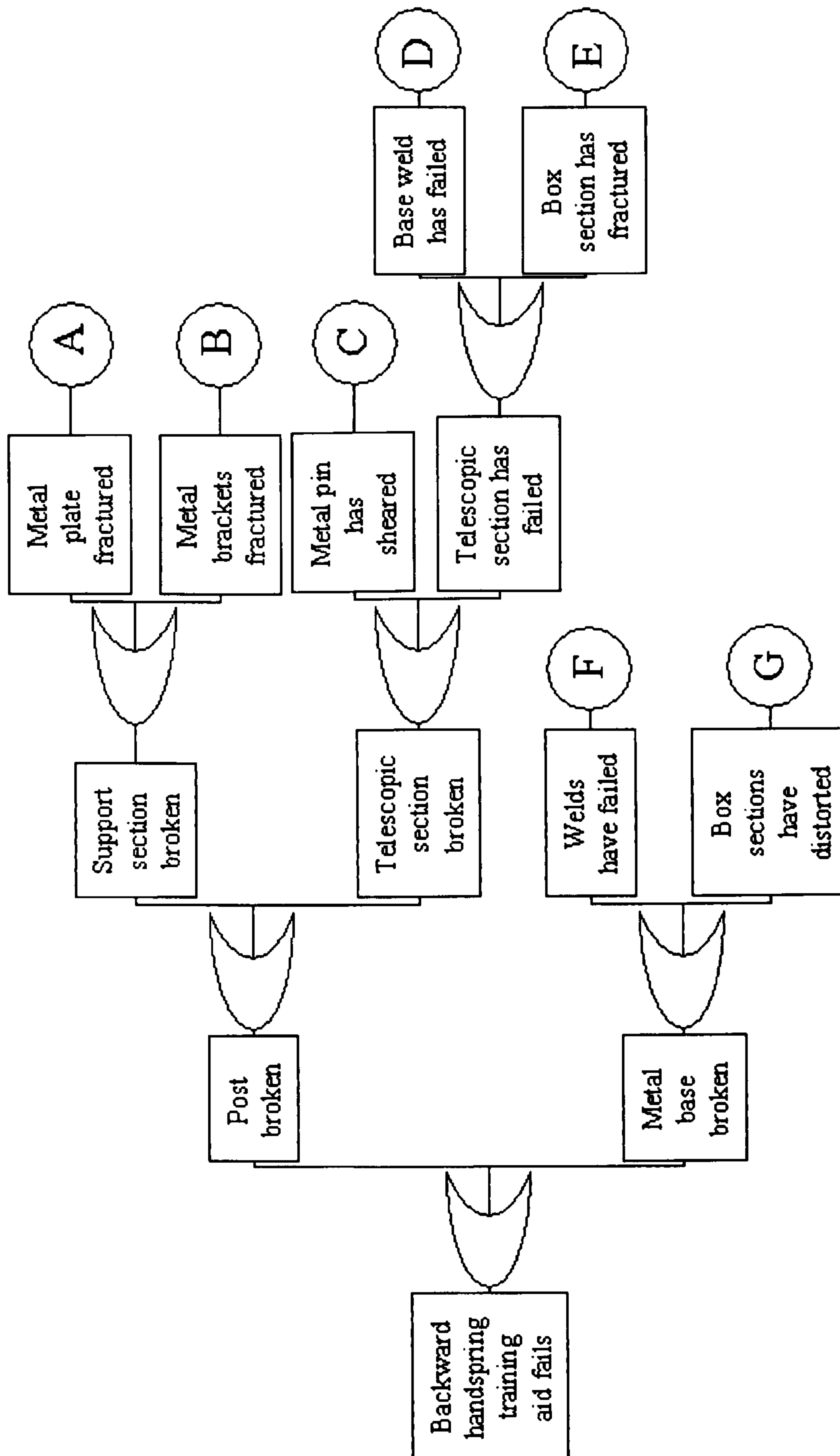


Figure 8-25: Fault tree for the backward handspring training aid design.

Item	Description and function	Failure mode	Failure effects		Detection method	Severity (1-5)	Probability (1-5)	Remarks
			Local	System				
A	Support section metal plate: Provides main strength of this section	Bending or weld shear	Top section will become detached	Training aid rendered useless	Observation only	5	2	Design calculations performed to reduce probability
B	Support section metal brackets: Provides increased strength for the section	Buckling	Support section will lose its form	Training aid will become less effective and be at risk of further failure	Observation only	4	2	Design calculations performed to reduce probability
C	Telescopic section metal pin: Used to adjust the height setting of the training aid	Shear	Telescopic section will be incapable of having adjustable height settings	Training aid can only be used at minimum height	Observation only	3	2	Design calculations performed to reduce probability
D	Telescopic section base weld: Supports upright section	Shear	Telescopic section will become detached from the training aid	Training aid rendered useless	Observation only	5	1	Design calculations performed to reduce probability, two side braces also added
E	Telescopic section: Main structural component	Buckling, bending, or torsion	Telescopic section will fracture or become deformed	Training aid rendered useless	Observation only	5	1	Design calculations performed to reduce probability
F	Metal base welds: Join the base structure together	Shear	Base will become misshapen	Training aid rendered dangerous	Observation only	4	1	Base is permanently on a flat floor so forces are minimal
G	Metal base box section: Produce the base structure	Bending or torsion	Base will become misshapen	Training aid rendered dangerous	Observation only	4	1	Base is permanently on a flat floor so forces are minimal

Figure 8-26: FMEA work sheet for the backward handspring training aid.

Due to the designed safety factors the probability of all the failure modes is low. The two most critical points of failure were considered to be at the base, and at the top of the upright section, the two regions of maximum force application. The base of the metal frame would be subjected to relatively little force as it was flat to the ground providing the structure with considerable support. In the case of the metal frame tipping, there would be some force applied through the framework and welds, but these would still be minimal compared to the forces at the two ends of the telescopic section. It was therefore important that the possible modes of failure be considered for both the top and bottom joints of the telescopic section.

The worst possible scenario is that the gymnast will collide with the training aid perpendicular to the upright column as previously discussed as this would create the largest moments and forces. This could invoke several different modes of failure. The possible bending stress and shear stress at the bottom of the telescopic section have already been calculated, a similar analysis must now be performed for the support section. The possible modes of failure for this section are:

1. The support section will be sheared off the telescopic section :

Assuming the support section is merely welded straight onto the top of the column with no other support, the applied force P will be transferred directly on to the welded plate (Figure 8.28). The shear stress involved in this collision must be calculated and compared to the relevant weld strength between the top support section and the upright column to which it is attached:

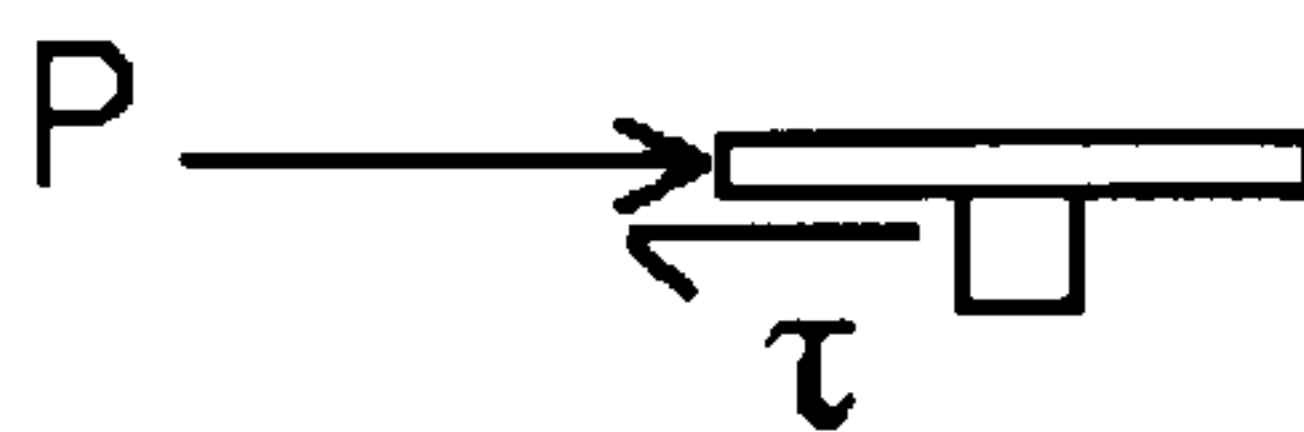


Figure 8-27: Forces involved if the top section is to be sheared away from the telescopic section.

If it is assumed that the support section is welded directly onto the face of 40mm square stainless steel box section, with a thickness of 2mm:

$$\sigma = \frac{Q}{A} = \frac{700}{3.04 \times 10^{-4}} = 2.30 \text{ MPa, which is well within the predetermined limits of the weld strength, 258MPa.}$$

2. The brackets in the support section will buckle:

With the brackets in place in the curved profile of the support section (see Figure 8.16), if the profiled metal plate of the support section is assumed rigid, the applied force P will be transferred through the plate directly into the three brackets. With the brackets fixed at both ends, buckling calculations must be performed to establish if they will fail in this environment.

If the brackets are considered to be rectangular with the dimensions 75mm x 15mm and are 3mm thick stainless steel, and a force of 700N applied directly through one of the brackets as a worse case scenario (Figure 8.29) then:

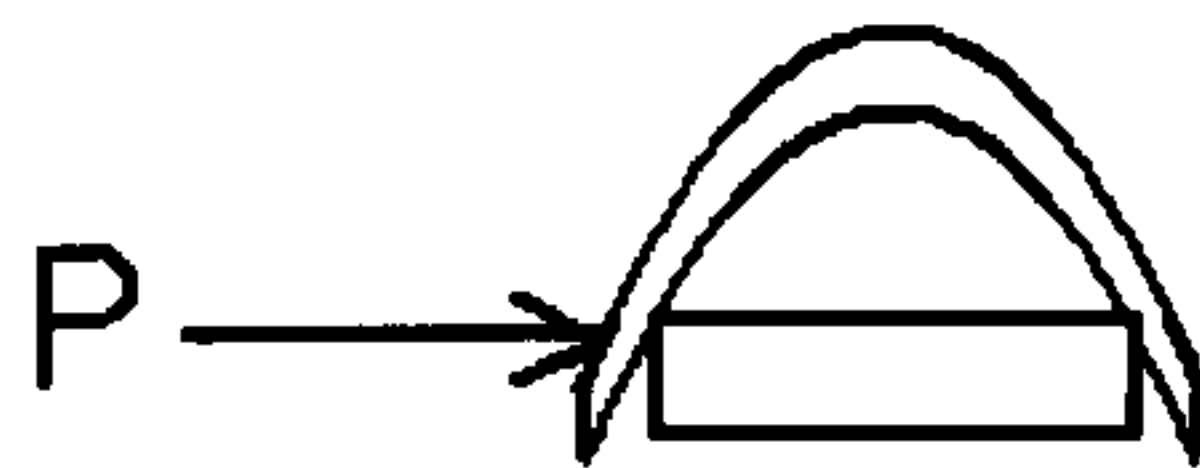


Figure 8-28: Forces involved in the top section is to buckle.

$P_c = \frac{\pi^2 EI}{4L^2}$ (Hibbler, 2004) where P_c is the critical load for buckling, L is the length of the section, E is the Young's modulus (196GN/m^2) of the material, and I is the second moment of area (Benham et.al, 1999):

$$P_c = \frac{\pi^2 \times 196 \times 10^9 \times 8.44 \times 10^{-10}}{4(75 \times 10^{-10})^2} = 72.56 \text{ KN}, \text{ which is one hundred times the magnitude}$$

of the expected applied force.

3. The profiled metal plate will deform:

If we assume that the profiled plate of the support section is in fact a single rectangular plate, and is supported in only two places rather than the three brackets, if the section between the two supports is directly loaded by the applied force P , the bending moment of this applied force must be calculated and the bending stress of the plate calculated to establish if there will be failure.

If the plate is assumed to be 500mm long, 30mm wide, and 4mm thick, with an applied point force of 700N in the centre of the plate (Figure 8.30):

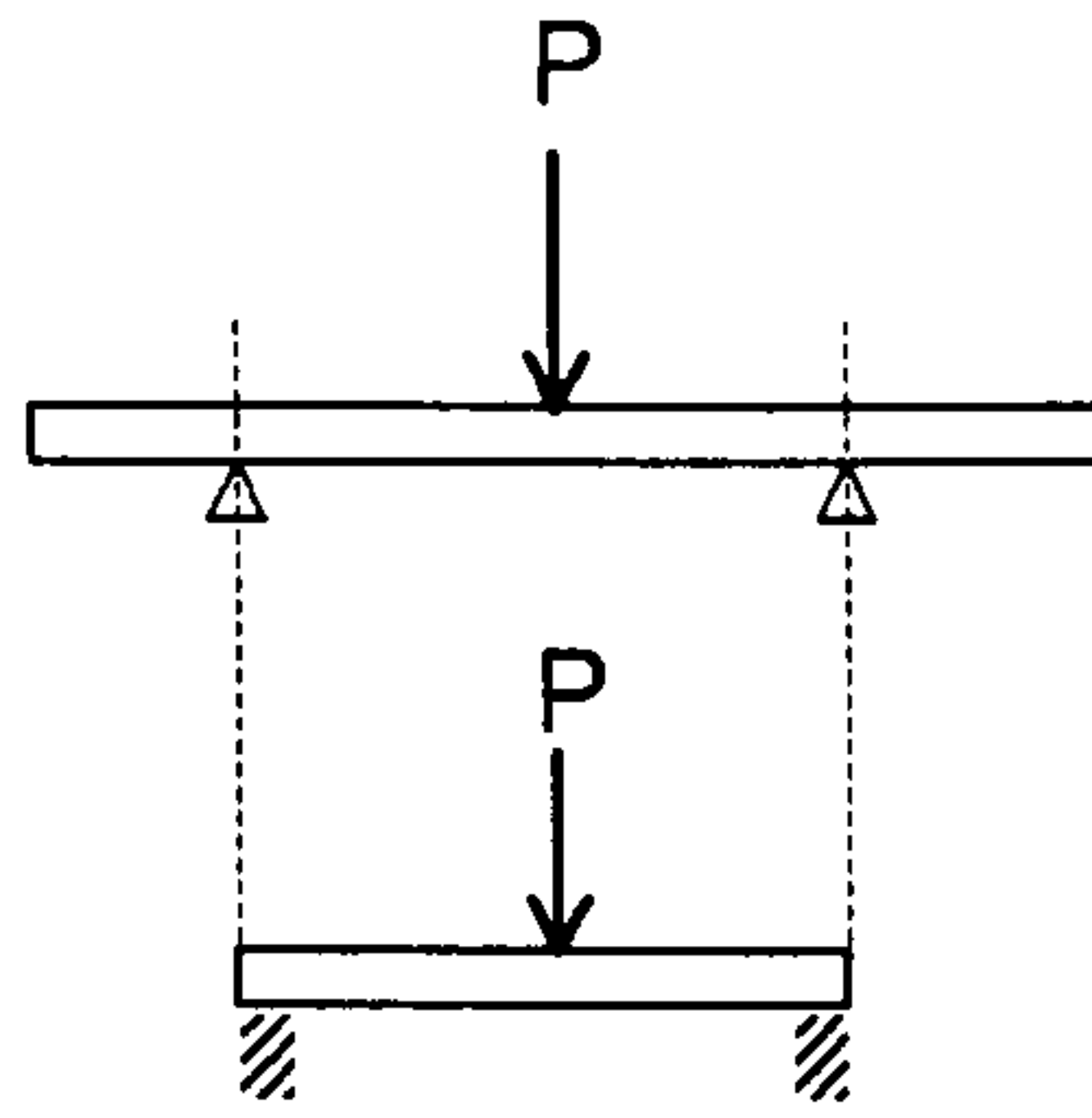


Figure 8-29: Bending moment of profiled plate scenario.

Maximum bending moment = $PL/4$ and the maximum shear force = $P/2$ (Matthews, 2004).

$$BM = 700 \times 128.2 \times 10^{-3} \div 4 = 22.44 \text{ Nm (2.d.p)}$$

$$\sigma = \frac{Mc}{I} = 22.435 \times 20 \times 10^{-3} \div 9 \times 10^{-9} = 49.85 \text{ MPa}$$

$$Q = 700/2 = 350 \text{ N}$$

$$\sigma = \frac{Q}{A} = \frac{350}{30 \times 10^{-3} \times 4 \times 10^{-3}} = 2.92 \text{ MPa, which is within the pre-determined weld strength}$$

for stainless steel, 258MPa.

Combining the bending and shear stress as before to calculate the Maximum Principal Stress using Mohr's stress circle calculation method:

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \frac{1}{2} \sqrt{[(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^2]} = 50.02 \text{ MPa, which is within the criteria of von}$$

Mises (Benham et. al, 1999), the Maximum Principal Stress for this scenario is much lower than the Yield Stress 276MPa of general purpose stainless steel (Matthews, 2004).

The other possible mode of failure not yet considered is if the impact force P is applied to the outermost edge of the support section, and torsional forces are introduced. The torsional forces could either induce shear stresses at the top of the telescopic section where the support section is attached, or the torsion could descend down the telescopic section and affect the joint between the telescopic section and the base of the metal frame.

Torsion calculations

If the force is applied directly onto the support section, and no force is transmitted to the rest of the system (Figure 8.31).

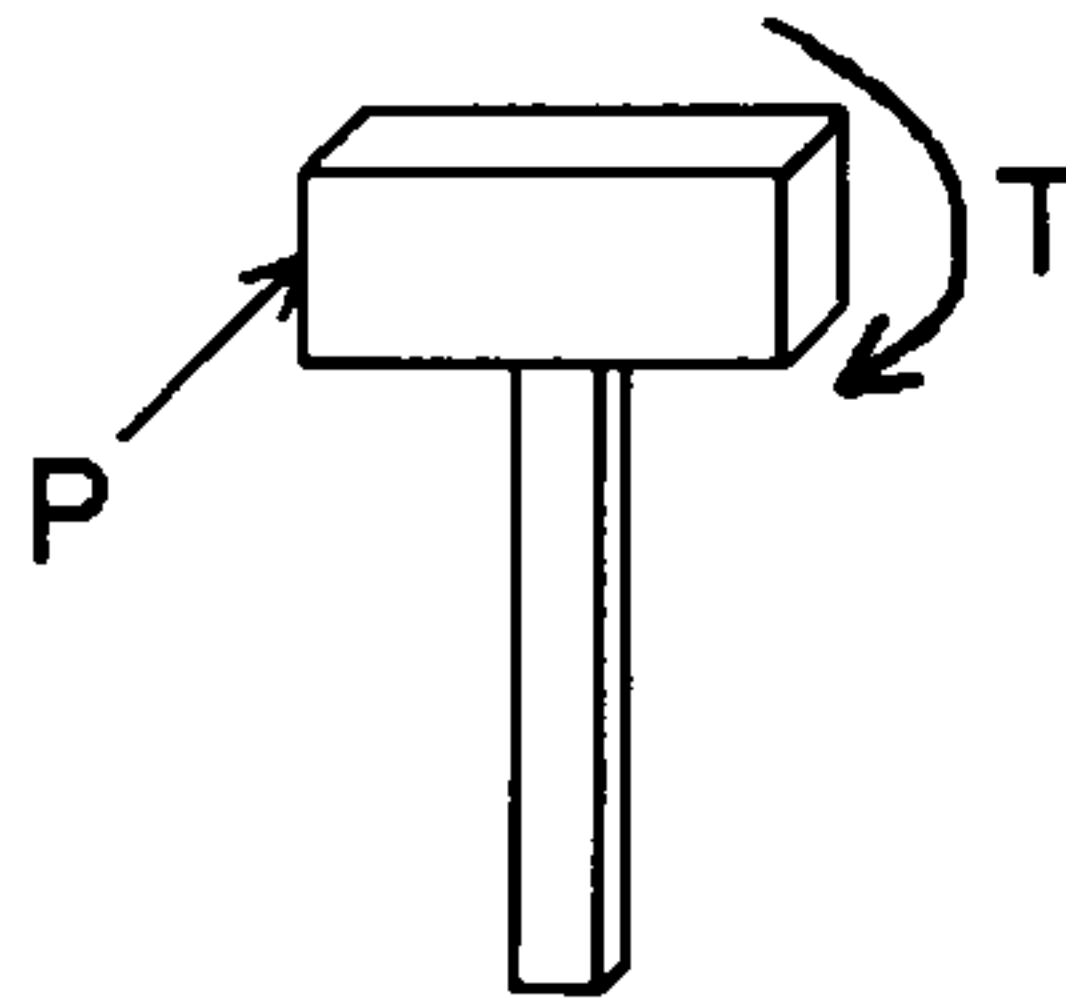


Figure 8-30: Application of torsion onto the support section.

If the top support section is 500mm wide, and is attached to the 40mm square, 2mm thick stainless steel box section:

$$M = 700 \times 250 \times 10^{-3} = 175\text{Nm}$$

$\sigma = \frac{Mc}{I} = 175 \times 2 \times 10^{-3} \div 5.312 \times 10^{-9} = 65.89\text{MPa}$, which is within the pre-determined strength boundary of the weld (258MPa).

If the applied torque is assumed to be transmitted directly down the telescopic section, and the telescopic section is again assumed to be a single column of 40mm square 2mm thick box section with no supporting brackets as a worse case scenario (Figure 8.32), then the torsional force will attempt to shear the weld at the bottom of the telescopic section:

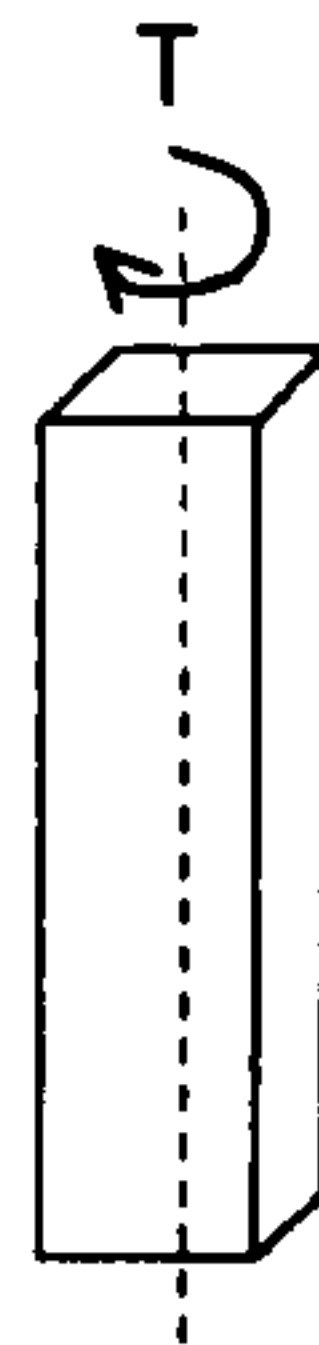


Figure 8-31: Application of torsion onto the telescopic section.

For a square box section, shear stress can be calculated from:

$\tau = \frac{T}{2At}$, where T is the applied torque, A is the area enclosed by the centre-line of the wall of the tube, and t is the thickness of the box section (Benham, 1999).

$$\tau = \frac{T}{2At} = 175 \div [2 \times (39 \times 10^{-3})^2 \times 2 \times 10^{-3}] = 28.76\text{MPa}, \text{ which is also within the}$$

boundary of the predetermined weld strength for stainless steel.

With the metal frame designed, and with the failure analysis complete, it was safe to continue with the rest of the design. Although the calculations have all been

approximations of the actual environment, they have shown that the structure is strong enough to warrant manufacture. Once the prototype is fully designed and manufactured safety testing prior to any gymnastics use will be carried out practically to ensure that the equipment is safe for use.

8.5.4 Design of the seat section and post padding

Foam padding was to be used to produce the final shaping of the training aid, and also to provide padding for the metal structure beneath. As was discussed earlier, the support section was designed to be covered by two different foams, one with high density foam (38kgm^3) to absorb high impact forces, and the other with lower density foam (20kgm^3), a softer, spongy foam for comfort (Gymnova, 2003). The supported section was then also covered by a 50mm thick mat draped over the top, not only adding to the top padding, but also covering any of the exposed metal frame at the rear of the structure. The mat was designed to be the same 500mm width as the supporting section of the training aid to permit the gymnast to swing the arms during takeoff, and was also designed to be the correct length to be level with the floor at the minimum height, and to also cover the metal structure at the maximum height. The foam densities have been taken from the foams used by Gymnova for other training products.

Additional foam padding was also added around the bottom segment of the telescopic section to provide further safety for the gymnast in the case when they undercut the backward handspring and hit the post with the fingers, or at worst the head. This padded section also reduced the required length of the overhanging mat as it covered the bottom section of the frame at minimum and maximum height. Neither the additional padding, or the overhanging mat padding encroached in any way into the free *igloo* space.

The seat section of the training aid was the final section to be designed. The required dimensions had already been established during the initial analysis of the performance parameters in Section 8.4.1. As the seat depth increased at a different rate to the seat height, it became apparent that the initial concept of adding sections of foam to the seat section to adjust the training aid between sizes was not viable. This concept also meant that large quantities of foam would remain unused when the training aid was set up for small gymnasts, and the foam sections could end up lost around the gymnasium or the coach may not piece together the seat correctly. The concept was rejected due to the waste of material, complex equipment adjustment for the customer, and the danger of the training aid quickly becoming unusable by taller gymnasts if pieces of foam were misplaced

It was decided that the foam set would be designed in tiers. The bottom seat would be made the required dimensions, the middle seat would fit flush on top of the smallest seat, producing a medium sized seat of the required dimensions. This would then be repeated once more for the largest seat. This would result in there only being two extra pieces of foam when the training aid was at its minimum height, and only one when at the medium setting. The foam sections were large enough that they would not become misplaced, were specifically profiled so that they would only fit together one way, and were only usable for the intended purpose for safety considerations. The final alteration to the seat profile was to chamfer the leading edge of the seat to encourage the gymnast to sit back into the seat. This would also prevent smaller children from trapping the edge of the seat behind the knees during the squat in the backward handspring.

8.5.5 British Standards requirements

The British Standards reviewed within the literature survey in Chapter 2 must be considered within the design. As in Chapter 5 the materials used should meet the required fire standards, and should have suitable frictional properties. As standard Gymnova materials will be used which are already in use within existing training aids together with equipment available on the market which will have been certified by British Standards test centres it will be assumed that the materials used are suitable for use and will pass British Standard requirements.

With regards to structural safety and integrity, the training aid must have no sharp edges or protruding parts. There must be no shearing or crushing points, and no danger through unintentional dropping of the equipment. The equipment must be stable, strong, and shock absorbent, and withstand British Standards testing (BS EN 913:1996).

8.5.6 Final design

The final design was modelled in Unigraphics, all dimensions were checked, and the design was produced as a solid model (Figure 8.14). Full engineering drawings were provided to Gymnova, with images of relevant 3D views of the training aid.

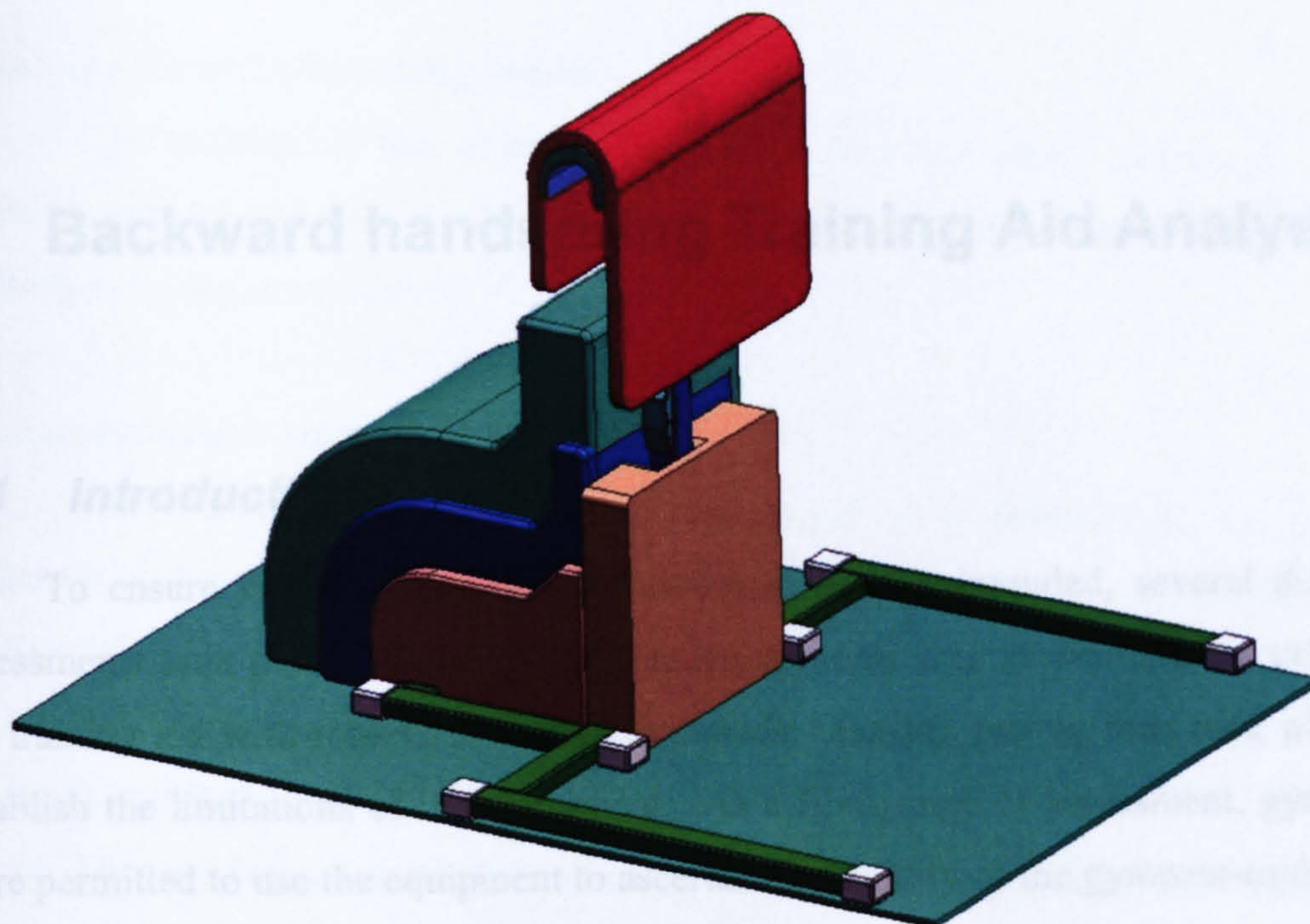


Figure 8-32: Final design concept.

8.6 Chapter summary

The training aid has been designed to support a gymnast whilst learning a backward handspring. It has not been designed to support gymnasts already capable of performing a backward handspring unaided as this may lead to complications between different techniques.

The training aid has been designed to meet British Standards, a general failure analysis has been undertaken, and all feasible safety aspects have been considered. The training aid prototype, once produced, will be tested practically to substantiate the failure analysis, and further testing will be carried out to ensure British Standards conformity.

The training aid has been designed from data collected from high level gymnasts and will be tested by a larger sample of suitably high level gymnasts.

9

Backward handspring Training Aid Analysis

9.1 Introduction

To ensure that the training aid functioned as was intended, several different assessments took place. The first of these assessments was to evaluate the safety of the training aid with respect to British Standards. Further testing then took place to establish the limitations of the equipment. As a final stage of assessment, gymnasts were permitted to use the equipment to ascertain the quality of the gymnast-equipment interface.

9.2 Safety testing

Several different methods of safety testing took place during the testing of the training aid. No athlete was permitted to perform on the training aid until a full safety and risk assessment had been completed.

9.2.1 British Standards safety testing

The most relevant of all the British Standards reviewed was BS EN 913:1996; Gymnastics equipment – General safety requirements and test methods. It was ensured that the prototype training aid closely adhered to the complete checklist contained within the *General safety requirement*, section of EN 913:1996.

Surface Finish

All surfaces were machined to the required finish, all corners were rounded off, and most of the metal structure was then also covered with the foam seat when in use. Any protruding parts of the frame were covered with rubber feet, or were made from plastic and were covered by the overhanging mat so as not to permit any damage to the gymnast.

Gaps and Shearing/Crushing Points

The training aid was composed of a metal structure which had no gaps which were considered as a risk of entrapment, and there were no shearing or crushing points anywhere on the structure.

Unintentional Dropping

Unintentional dropping was not considered as a problem as no transport system was to be used to move the training aid as it only has a mass of 16.5kg in total (without the mat or foam section as these were detachable).

Strength and Stability

The training aid was tested in accordance with Annex B of EN 913:1996.

Testing procedure: The training aid was firmly attached to a Kistler force platform via a rigid wooden platform and a series of bolts, in the same manner as was detailed for the handstand training aid in Chapter 6. The average horizontal and vertical forces were then measured during typical use. These forces were then statically applied to the training aid and deformation and tipping was measured in accordance with the methodology detailed in BS EN 913.

Results: The average horizontal force during normal use was measured to be 13.3N; the average vertical force achieved during normal use was measured to be 45.3N.

In accordance with BS EN 913, these loads were applied statically for the duration of 1 minute (+0.1s). After 30 minutes (+30s), the deformation was measured to be 0.00mm, and no tipping or sliding occurred.

The training aid had been designed to tip slightly during dynamic usage to reduce impact forces on the body during a poorly performed repetitions. However, it had also been designed so that if it did tip during use, it would always return to a stable upright position once the '*tipping*' force had been removed.

Adjustment Devices

There was only one adjustment device fitted to the structure of the training aid and it was a standard gymnastics equipment component which had been designed to prevent accidental adjustments from taking place during use.

Shock Absorption of Top Padding

The training aid was tested in accordance with Annex C of EN 913: 1996. For this test, an 8kg metal indenter, with a diameter of 78mm and a bottom radius of curvature of 500mm was used. The indenter had an accelerometer rigidly mounted to the top of the metal indenter and was dropped from 1m above the top of the training aid directly down onto the top padded section. The test was carried out 5 times at the same location, at intervals of 2 minutes. The average deceleration was measured to be 429.68 m/s^2 (43.80g).

Conclusion

Although the training aid has been tested using methods outlined within the British Standards EN 913:1996, and had met all standards required, it would be necessary that the manufacturer of this training aid also had the equipment fully assessed at a British Standards test centre once the first model had been manufactured through production tooling.

9.2.2 Further impact and stability testing

Further testing, far beyond the requirements of the British Standards requirements was also carried out on the training aid. This testing comprised several different assessments which were deemed more suitable for testing the training aid prior to gymnast interaction than the generic non-gymnastics specific tests set out by the British Standards.

Stability Impact Testing

Three tests were carried out to assess the stability of the training aid. These tests consisted of pendulum impact tests, during which varying masses were swung at or dropped onto the training aid. The testing procedures were recorded with a high speed digital video camera, at 500Hz. These video images were then digitised, permitting further analysis of the response of the training aid to the tests performed.

Top impact: 20-65kg masses were dropped vertically downward, directly on to the top of the training aid. This was to simulate a gymnast landing directly onto the top of the equipment. The stability of the training aid, and any deflections in the metal structure were to be observed and recorded. On all tests the vertical post and top

padding acted as a spring-damper system, and the masses rebounded as the structure remained stable. At 65kg, the training aid rebounded off the ground to approximately 17mm (± 1 mm), but quickly returned to its original static position. The training aid was tested to be safe to 65kg for vertical top loading. Higher loads were not tested as it was deemed unsafe to test due to having to lift the unsecured load manually.

Side impact: 20-75kg masses were attached to the laboratory roof joists using rope, and were pendulum-swung into the training aid so as to make a contact angle of approximately 45° downwards to the front of the padding. This was to simulate a gymnast diving back over the training aid but making contact due to a lack of height in the performance. With a pendulum mass of 75kg, swinging under gravity, the training aid tipped, the front feet of the training aid lifted to an angle of 20° ($\pm 1^\circ$) from the horizontal. The back feet did not move, and the training aid returned to its static vertical position.

Front impact: 20-65kg masses were attached to the laboratory roof joists using rope, and were pendulum-swung from behind the training aid so as to make contact with the front of the training aid padding. This was to simulate a gymnast driving back training into the upright section of the structure. At 65kg, the training aid tipped to an angle of 5° ($\pm 1^\circ$) and then slid backward by approximately 320mm (± 1 mm). Although the training aid moved backward it returned to an upright position, and under these circumstances a gymnast would still have been safe. The gymnast would have ended up either sitting on the foam seat, or rolling off the back of it, they would not have moved backward with the training aid.

During all of the testing, although the training aid was only safety tested to 65 or 75kg, in all the situations assessed the gymnast would still have had a large proportion of their mass on the foam seat section which would massively reduce the overall force that the backward handspring could inflict upon the training aid. For the front test, the gymnast would still have had his or her feet on the floor so the force directed back into the training aid would be only a fraction of this size.

Ergonomic Testing

The second phase of the testing was to have an experienced gymnast perform some basic preparatory exercises on the training aid. This would establish the comfort of the training aid, and assess how it responded during actual use.

The gymnast who performed this skill (gymnast E) had a body mass of 60kg and had 20 years experience at performing backward handsprings. She was a National

level Sports Acrobat, and was also a club level gymnastics coach. The preparatory exercises were videoed using a high speed camera recording at 500Hz to permit further analysis of the equipment-gymnast interaction.

The gymnast performed two main exercises. The first was a *fall-bend-extend* series. This included phased 1 and 2 of the backward handspring as discussed in Chapter 7 (Figure 7.1). During this preparatory exercise the gymnast simply drove her shoulders back into the training aid with just the power from her legs and hip flexors, her feet remained upon the floor. This exercise is commonly used when first teaching the early stages of a backward handspring. The exercise induced a strong backward force into the front of the training aid as the gymnast made contact with her upper back. The gymnast experienced no discomfort whilst performing this exercise, and the training aid showed no signs of slipping or tipping. Very little compression of the top padding was observed from the high speed video, the training aid performed exceptionally well during this assessment.

The second of these exercises was similar to the first but followed with a *jump*, so that the gymnast dived back over the training aid landing with the small of her back on the top padding (phases 1, 2 and 3). This exercise was performed in stages of increasing power until the hands of the gymnast almost reached the floor on the other side of the training aid. This exercise is normally performed with a coach supporting the gymnast and catching the full body weight of the gymnast in the coaches arms. With a gymnast of body mass 60kg, this would be difficult without two strong coaches.

When the exercise was performed over the training aid at 100% effort, the gymnast landed with her whole body suspended in the air, with her hands a few centimetres from the floor. No discomfort was experienced in any way during these performances and the gymnast reported to have felt no movement. There were however very slight movements of the training aid observed from the high speed video. On analysis, the front feet of the training aid were measured to have lifted 13mm (± 1 mm), and tipped through an angle of less than 1°. As soon as the gymnast had come to rest on top of the padded section of the training aid the structure had returned to its initial stationary position with all feet on the floor.

9.2.3 Primary collision analysis

Before any gymnast was permitted to use the training aid fully it was decided that for safety reasons an initial collision analysis should be performed on the training aid. This did not necessitate any gymnast-training aid interactions, instead ten Regional-National level gymnasts were asked to perform a standing backward handspring which was recorded using a standard 50Hz digital video camera. The gymnasts ranged in age from 8-16 years, and in standing height from 1249-1708mm. Parental permission was acquired before any performances took place, and a coach was present at all times.

Prior to the video capture of the gymnast's performances, images of the training aid at the three differing height settings were obtained with the training aid in the same capture volume and with the exact same camera setup.

Using a sports video analysis program, Dartfish, the backward handsprings performed by the gymnasts were superimposed over an image of the correct size of training aid. The videos were then played at half speed, and if the backward handspring made contact with the training aid, the position of impact was recorded. All of the backward handsprings performed were also judged by an International Judge, and notes were made on each performance.

Following this investigation, it became obvious that if the backward handspring was performed short and loopy, with the gymnast's head moved backward away from the recommended neutral position, it was possible that the head of the gymnast may collide with the top padded section of the training aid. Due to this discovery, it was decided that a 'recommended program of use' should be compiled as an extra section to the training aid risk assessment. All other collisions observed with the training aid were as expected. Shoulders hit the front side of the padding on the training aid when the backward handspring was too low, and the small of the back hit the training aid during the flight when the backward handspring was too short. Both of these situations had been predicted, and the training aid had been designed accordingly to support these collision types.

9.2.4 Risk assessment

It was crucial that a full risk assessment was performed before any gymnast was permitted to perform a backward handspring over the training aid.

Firstly, the risk of the training aid failing to meet the requirements of the product design specification was calculated (Table 9.1):

Table 9-1: Risk of technology failure

Technology difficulty	Risk factor (Rd)
We are using existing technology with which we have personal experience, in an application identical to the one proposed.	1
We are using existing technology with which: (1) we do not have personal experience or, (2) In an application different to the one proposed.	2
We are making a new development with which we have personal experience in an application close to the one proposed.	3
We are making a new technology with which we have no personal experience or in an application different to the one proposed.	4
We are developing new technology in an area where we have little or no previous experience.	5

The company who manufactured the prototype training aid, Gymnova, had significant experience in designing and building safe training aids, but the backward handspring prototype was a new design. Therefore the risk of the technology failing to meet the design criteria was considered to have a risk factor of 3. Next to be assessed was the probability of the design failing (Table 9.2).

Table 9-2: Risk of design failure

Probability of design failure	Risk factor (Rf)
Will not occur during predictable lifetime of the design, regardless of any foreseen abuse of lack or maintenance. The design team have experience of the reliability of this component, all aspects of the design are under the control of the design team.	1
The design team are familiar with the application of the design in a similar situation and are confident that there is a low chance of failure irrespective of any foreseen abuse of lack or maintenance. All aspects of the design are under the control of the design team.	2
The design team are unfamiliar with the reliability of the design	3

with regards to failure modes. However a third party supplier or corroborated information from else where suggests the reliability is acceptable.	
Uncorroborated evidence suggests the design will provide acceptable reliability in regards to failure modes being considered.	4
There are doubts about the reliability of this design in regard to the failure modes being considered.	5

As the training aid has purposely been designed to incorporate standard equipment components where possible, Gymnova were familiar with the majority of the components used within the training aid, and were therefore confident of a low chance of failure, the risk factor was therefore 3.

If the technical difficulty was then multiplied by the risk of the actual training aid mechanically failing, the project risk was calculated to be: $R_1 = R_d \times R_f = 3 \times 3 = 9$ from a possible scale of 1 – 25. The consequence of the failure of the training aid to the safety of the gymnast could now be considered (Table 9.3):

Table 9-3: Consequence of failure to the gymnast

Consequence of failure to gymnast	Risk factor (Rc)
It the technology fails to provide the required performance it will either: (1) There will be no improvement in the gymnast ability, or (2) A coach will still be required.	1
Failure of the technology will mean that The backward handspring may be learnt with the wrong technique.	2
If the technology fails there is possible risk of: (1) slight injury, or (2) Increased anxiety for the gymnast.	3
If technology fails there is possible risk of significant injury.	4
If the technology fails there is certainty of significant injury.	5

The risk of equipment failure, with regards to the safety of the gymnast was considered to have a value of 4. If the risk to the gymnast was now calculated: $R_2 = R_f \times R_c = 3 \times 4 = 12$. This risk would be reduced by significant safety and failure testing taking place before any gymnasts are permitted to use the training aid. This

would therefore reduce the risk factor R_f to 1. As the majority of this safety testing has already been carried out and detailed in Sections 9.2.1-9.2.3, the new risk would therefore be: $R_2 = R_f \times R_c = 1 \times 4 = 4$.

Considering now how the influence of poor technique performed by the gymnast whilst using the training aid could affect the gymnast's overall safety, it became obvious that as mechanically safe as the training aid was structurally, if the gymnast still performed the skill with a dreadful technique, then there was still a risk of injury (Table 9.4):

Table 9-4: Consequence of poor technique used by the gymnast

Consequence of poor technique used by the gymnast	Risk factor(R_t)
<p>It the technique is weak.</p> <p>(1) The gymnast travels backward but fails to create enough horizontal velocity (U_0 – Figure 7.4, Chapter 7) during the performance. This will result in the shoulders or back of the gymnast will land on the top of the training aid, or</p> <p>(2) If the gymnast does not develop enough vertical velocity (V_0 - Figure 7.4, Chapter 7) the shoulders of the gymnast will push back into the front side of the training aid.</p>	1
<p>The gymnast performs a good but slightly low backward handspring, then he/she will clip the shoulders on the front of the training aid, and the lower back on the top of the training aid. The backward handspring will remain dynamic.</p>	2
<p>The gymnast performs a good but low backward handspring, then the gymnast will land with the middle of their back over the training aid, hands either suspended above the floor, or in contact with the floor, but with minimal loading.</p>	3
<p>The gymnast performs a loopy backward handspring and cuts the hands back under the shoulders:</p> <p>(1) The hands will hit the back side of the training aid and may stop rotation at that point; the gymnast may land on the knees.</p> <p>(2) The gymnast may have the head stuck out and this may come in contact with the back side of the training aid again stopping rotation and leading to the gymnast collapsing on landing.</p> <p>Hands will make first contact with the floor in these cases.</p>	4

The gymnast does not set the backward handspring back, pushes the knees forward in takeoff and gains the backward handspring. This can result in the gymnast landing on their head on the top of the training aid.	5
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Due to this risk factor Rt being high a value of five was awarded for this category of risk. It was therefore decided that to prevent injury when using the training aid, no gymnast should be allowed to use the training aid unless having been through the training procedure.

Recommended programme for use

1. The gymnast must perform several 'dive-backs' over the training aid, supported by a qualified coach until they are aware of the position of the vertical supporting post.
2. The gymnast must then repeat dive-backs, gradually building power until they are landing on the hands at the far side of the training aid safely. This must still be overseen by a coach.
3. Once competent at the dive-back alone, and confident with the performance, the gymnast may perform supported backward handsprings over the training aid. Extra matting may be used at the back of the training aid for landing if wished.
4. Once fully competent and completely clearing the training aid, the gymnast may progress to unsupported backward handsprings, overseen by a coach.
5. When confident the gymnast can work on the training aid alone, but only in conjunction with a coached session.

The training aid had been developed to help the learning of the backward handspring, and had not been designed to replace a coach. It should therefore be used alongside the standard supporting and shaping carried out by the coach. The main purpose of the training aid was to permit repetitions of the backward handspring, and its progressions, whilst providing feedback. Use of the training aid should always be supervised, and the gymnast should be supported on the training aid until it is agreed by coach and gymnast that it is safe for the gymnast to practise unsupported.

It is not intended that gymnasts inexperienced with the training aid, should be able to simply perform a backward handspring over the training aid when asked.

There are psychological factors involved in such a change in environment, and there is nothing to guarantee that the gymnast in question has a backward handspring with an *igloo* of the correct shape to clear the training aid. This would be an unsafe procedure.

9.2.5 Initial gymnast - equipment interface analysis

Once all risks associated with the use of the training aid had been established, and a programme for use had been compiled, it was deemed safe for an experienced gymnast to perform supported backward handsprings over the training aid.

The equipment and training program was again analysed by gymnast E. The gymnast closely followed the training programme, and when at the stage of performing a supported backward handspring over the training aid for the first time wore a gymnastics safety harness and was supported by a qualified coach. Once she had become accustomed to performing the skill over the training aid, the harness was removed and the gymnast performed several free backward handsprings over the training aid without any difficulty.

It is considered that the training aid may have been approximately 50mm too high for this particular gymnast as during the flight phase of the skill she 'clipped' her shoulders on the way up, and her lower back on the way down. This contact however did not affect the dynamics of the skill performed, and the skill was still considered a technically good, and safe skill.

9.3 Pilot study

As it can prove complicated to get relevant participants and their coaches to attend data collection sessions, it is of the utmost importance to ensure that the data collected is of a high quality and is complete. It is therefore good practice to run a pilot study to ensure that the methods of data collection proposed are effective, and that all of the required data is obtained within the session.

9.3.1 Vicon data collection

It was proposed that the Vicon motion analysis system would be used to collect displacement data of the gymnast's joint centres to enable a comparison of joint angles between a free standing backward handspring and skills which were

performed over the training aid. A single digital video camera was also used to collect standard 2-dimensional video of the performances side-on. This was to produce a visual record of each performance. The gymnasts would be supported as it would not be possible to give them enough time to become sufficiently familiar with the training aid for it to be safe for them to perform the skill on their own.

During the data collection each gymnast performed five standing backward handsprings without the training aid present, then starting in the same position performed a further five supported backward handsprings over the training aid. The training aid was adjusted to the correct setting for the individual standing heights of each gymnast.

Twenty-two markers were positioned over the body and anthropometric measurements of joint centre offsets from marker centres were also recorded. This was to enable the joint centre locations to be determined when post-processing the data.



Figure 9-1: Marker placement for Vicon data collection.

When reconstructing the marker data using the Vicon workstation, it was discovered that when the gymnast was in flight over the training aid, there was such a small gap between the back of the shoulders and the top of the training aid that the Vicon cameras were incapable of tracking the markers during this phase of the movement. The markers only reappeared once the hands had made contact with the floor and the gymnast began the second phase of the skill.

As this section of the skill was crucial to enable a full analysis of the training aid, it was decided that as the skill could be accurately considered as a planar movement, and it was appropriate to digitise the joint centres using the Silicon Coach Digitising program. The digital video collected was suitable for digitising and the joint centres could be clearly identified when the individual frames were magnified. As the backward handspring is not a particularly high speed skill, and involves only a steady movement pattern, 50Hz was an adequate video collection frequency for digitising this skill.

It was decided that for efficiency and accuracy, digitising would be used for the extraction of movement information during any further data collections.

9.4 Data collection

The main data collection was carried out using a total of twenty-one Regional-National level gymnasts. These gymnasts ranged in age from 8-21 years, and a standing height range of 1249-1708mm. Parental consent was obtained for all gymnasts participating in the data collection. The skills were all performed in the Loughborough Gymnastics Centre on the tumble track.

9.4.1 Further collision analysis

As all of the gymnasts at the data collection were capable of performing a standing backward handspring, it was imperative that only those who were capable of performing the skill with an appropriate *igloo* shape for the training aid were used for further analysis. Those gymnasts who performed the skill with an unsuitable *igloo* shape were in danger of colliding with the training aid without being taken back to preparatory exercises and relearning the skill using the training programme developed for the use of the training aid.

The assessment of which gymnasts were safe to use the training aid was achieved by using the Dartfish sports video analysis program in the same manner as the initial collision analysis. The unsupported skills were digitally videoed at 50Hz, and were then superimposed over the required image of the training aid and a collision analysis was performed.

From the twenty-one gymnasts videoed, when assessed using Dartfish, only eight gymnasts had a backward handspring of a suitable shape which did not collide with the training aid and therefore enabled them to participate in further analysis. These gymnasts ranged in standing height from 1249 to 1708mm, and so covered all three heights of the training aid.

9.4.2 Gymnast skill-preparation analysis

The eight gymnasts found suitable for participation were first coached through the training programme for use of the training aid. Once confident in the performance of the preparatory exercises the gymnasts were given time to familiarise themselves with performing on the training aid. During this time the exercises were videoed so that analysis could be performed on the individual interactions of the gymnasts using the training aid at the correct height.

The landing positions of the gymnast on the training aid during the *dive-back* exercises were analysed to ensure that each gymnast passed through the correct shape and that they landed in the correct position to avoid collision with the lower back and the training aid.

9.4.3 Main testing

Once the gymnasts had been given time to familiarise themselves with the geometry of the training aid, each gymnast was given time to practice performing a standing backward handspring over a small foam block in order for them to become accustomed to diving up and back over an object. Each gymnast then performed three supported standing backward handsprings over the correctly adjusted training aid, and this was followed by three performances of the skill without the training aid.

A landing mat was placed behind the training aid to cover the back legs and to soften the landing slightly. Each performance was digitally videoed at 50Hz to enable digitising to take place. To ensure that the skills were planar and therefore suitable for digitising, the gymnasts were provided with a straight line along which they were asked to perform the skill. All skills were judged by an International Judge and notes were made on techniques.

9.5 Data analysis

The pre-determined performance parameters (Chapter 7) were correlated against anthropometric measurements of the gymnasts. These relationship, alongside coach and gymnast feedback will now be discussed.

9.5.1 Methodology

From the data collected sixteen backward handsprings were analysed. The technically best performance (decided by an International Judge) with and without the training aid were chosen for each of the eight gymnasts. These performances were then strobe overlaid using Dartfish. From these images the four established performance parameters were extracted: sit height; sit length; position of maximum height of the first flight phase.

The digital video of the performances was then digitised using the Silicon Coach program and the data collected was saved to a database. The following points were digitised: wrist; elbow; shoulder; hip; knee; ankle; toe.

Once compiled, the files were processed by a Matlab programme which converted the co-ordinate data of the joint centres into joint angles using Pythagoras Theorem and trigonometric equations. The following angles were then calculated: elbow; shoulder; hip; knee; ankle. These angles were compared for the following specific chosen stages of the backward handspring: *takeoff*, as the toe tip left the floor; *maximum height*, which was defined as the highest point the skill reached whilst in the flight phase; *touch-down*, which was defined as the point when the hands created a depression in the floor surface, (and were hence load bearing) at the end of the first phase of the movement; *push-off*, the point at which the hands were no longer in contact with the floor in the second phase of the movement; *landing*, when the feet first came in contact with the floor, creating a depression in the surface, and were hence load bearing.

Data on the second phase of the performance was not collected from four of the eight gymnasts, and so here comparisons could not be made. This was because four gymnasts preferred to perform a backward handspring walk-out, over the training aid rather than a two-footed exit from the skill, meaning that a dynamic analysis could not take place.

9.5.2 Performance parameter comparisons

Table 9.5 below, shows the values of the four performance parameters: sit height (a), sit length (d), skill length (g), and skill height (c), for each individual gymnast (Figure 7.13). The table also contains the standing height of each individual gymnast and both the supported and unsupported performances are detailed. This information will later be analysed for each gymnast and explanations will be given for any variation between the supported and unsupported trials performed by each gymnast.

Table 9-5: Gymnasts measured performance parameters

Standing height (m)		sit height (a) (mm)	sit length (d) (mm)	Skill length (g) (mm)	Skill height (c) (mm)
Gymnast 1	On own	435	335	467	963
1.58	Supported	446	415	727	1202
Gymnast 2	On own	386	346	646	849
1.46	Supported	397	335	727	1028
Gymnast 3	On own	372	293	469	914
1.6	Supported	393	372	618	939
Gymnast 4	On own	375	317	589	762
1.43	Supported	424	289	577	990
Gymnast 5	On own	293	217	409	743
1.29	Supported	234	223	614	819
Gymnast 6	On own	392	353	626	995
1.71	Supported	380	304	657	1240
Gymnast 7	On own	408	369	490	778
1.55	Supported	413	352	710	1202
Gymnast 8	On own	370	306	542	1006
1.65	Supported	419	294	577	1159

From the data in Table 9.5, it can be seen that the general trends were: the sit height values remained very similar for the supported and unsupported performances for the majority of the gymnasts, any differences observed in the measured sit heights were small and the average increase in sit height was 1.9%; the sit length values showed a similar pattern, but with slightly higher discrepancies, the average increase in sit length was 2.4%; skill length generally increased in most cases, with an average increase of 25.6%; skill height increased for every gymnast, and had an average increase of 22.9%. These trends suggests that the seat section did not interfere physically or psychologically with the gymnasts; however the presence of the upright section encouraged a longer higher skill. In the majority of cases technique showed

improvement, but for some gymnasts it was apparent that they were attempting to 'clear' the training aid rather than perform their standard technique.

The following sections will focus on two gymnasts, gymnast 1 who performed a typical walk-out backward handspring over the training aid, and gymnast 5 who performed a typical standing backward handspring over the training aid. This will enable an in-depth analysis of the two skills, however data on the remaining six gymnasts can be found in Appendix G.

9.5.3 Joint angle comparisons

Tables 9.6, 9.7 and 9.8 below detail the joint angles: elbow, shoulder, hip, knee and ankle, at the different stages of the backward handspring: takeoff, maximum height, touch-down, push-off and landing, for gymnasts 1 and 5. These values permit a comparison of the performances both between gymnasts, and between supported and unsupported skills for an individual gymnast. Table 9.6 shows the data for the unsupported performance, Table 9.7 shows the data collected from the performance over the training aid, and Table 9.8 is a comparison of the two sets of data. The data will be discussed, and explanations will be suggested for differences between the supported performances (over the training aid) and unsupported performances (without the training aid).

Table 9-6: Joint angles in degrees for the individual unsupported performance

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	133	140	134	130	150
Max height	123	125	125	136	148
Touch-down	130	140	137	156	152
Gymnast 5					
Takeoff	151	141	140	126	142
Max height	127	119	116	110	133
Touch-down	138	154	166	107	101
Push-off	142	145	59	144	92
Landing	152	123	67	121	73

Table 9-7: Joint angles in degrees for the individual performances over the training aid

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	138	163	130	134	157
Max height	126	121	114	127	169

Touch-down	129	143	179	158	125
Landing	150	110	72	127	96
Gymnast 5					
Takeoff	150	140	146	145	143
Max height	136	131	125	133	145
Touch-down	138	129	150	162	141
Push-off	153	143	73	159	105
Landing	147	104	81	135	79

Table 9-8: Differences between the joint angles for the individual unsupported performance and the performance over the training aid

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	5	23	4	3	7
Max height	4	4	11	8	21
Touch-down	1	3	42	3	26
Gymnast 5					
Takeoff	1	1	5	19	2
Max height	8	12	9	23	12
Touch-down	0	25	15	56	41
Push-off	11	1	14	15	14
Landing	5	18	15	14	7

9.5.4 Discussion of results

It must be reiterated that the training aid was designed for a gymnast to learn a backward handspring. It had not been designed so that a gymnast already capable of executing the skill could immediately perform over the training aid without practice, as psychological factors and variations in skill technique could prevent this. Firstly the gymnast may not have learned the backward handspring in a style suitable for the training aid. Bad habits may have crept into the technique, especially if the gymnast only performed the skill as a linked series with the round-off, as the backward handspring requires slightly different technique when performed in a series, rather than from standing.

Although through discussions with gymnasts it had been conveyed that psychologically it is very reassuring to have a large solid but padded object behind you when attempting your first backward handspring, as it alleviates the anxiety of landing badly, it must be appreciated that this does not apply to experienced gymnasts. It will psychologically feel very different performing a well established skill in a completely new environment which involves physically diving over a solid object,

rather than performing the skill in a 'free-volume', and this was commented on by the experienced gymnasts involved in the study.

It was for these reasons that it is was expected that certain differences might occur between the supported and unsupported backward handsprings. This investigation is still very important, as it will provide information on whether a 'good' handspring can be performed over the training aid, or if a gymnast requires a totally different technique to perform the skill over the training aid, and it will also provide important gymnast feedback on their performances on the training aid. The two most crucial angles to be compared are the shoulder and hip, as these control the dynamics and shape of the gymnast during the skill. The angles of the ankle at takeoff and the elbow on touch-down may also be of further interest.

Gymnast 1

This gymnast felt more comfortable performing a 'walk-out' backward handspring, (as did three other gymnasts) when performing over the training aid, as she felt this skill was easier to perform from standing than a standing two-footed backward handspring. This meant that two different techniques were used, during a single trial, as she performed an unsupported accelerator backward handspring, and a supported walk-out 'floater' backward handspring when supported using the training aid. Only limited comparisons could therefore be made for this gymnast.

A 'walk-out' backward handspring involves splitting the legs as the hands make contact with the floor. It appears that this action can be performed either late once the hips have passed over the hands, or early before the hips get level with the hands. This is because the action of splitting the legs reduces the dynamic requirement of the backward handspring, permitting a low effort performance during the second phase of the skill.

Takeoff: During the takeoff phase, no real differences were be observed between the 'walk-out' performance and the accelerator performance. Gymnast 1 had a greater shoulder angle when performing over the training aid, but very little difference in any of the other measured joint angles. This suggested that the gymnast performed a similar take-off technique, whilst potentially attempting to create more height than in the unsupported performance. This may be explained by a lack of confidence in performing over the training aid.

Maximum height: At maximum height, gymnast 1 had a slightly smaller hip angle, all other joint angles were very similar between the two performances with the

exception of the ankle angle which was demonstrated a more extended foot during the performance over the training aid. The data suggested that this gymnast all had a very similar body configuration during both the supported and unsupported first flights.

Touch-down: During the touch-down gymnast 1 had a substantially larger hip angle and a more flexed foot. This however will have been due to the gymnast performing a walk-out backward handspring as discussed earlier in this section. The shoulder, elbow and knee joints showed no real differences between the performances

From this information it was concluded gymnast 1 showed no real differences in the first half of the skill, but still chose to perform a walk-out backward handspring. From the data obtained, it appears that the gymnast would have been capable of performing an accelerator backward handspring safely over the training aid with exactly the same takeoff as she executed in her second performances, had she chosen to.

Performance parameters: During the supported and unsupported performance, there was no substantial difference observed between the two sit heights of the performance of gymnast 1, however, the length of her sit increased during the supported performance. Both skill length and skill height also increased substantially during the supported performance. No conclusions can be drawn from this data as the two performances used different techniques.

Gymnast 5

Takeoff: The gymnast's knees were pushed back to straighten her legs more during the supported performance as the gymnast attempted to increase the length of the skill. This is a positive effect as the unsupported skill was slightly loopy. No other differences in joint angles were measured.

Maximum height: At this point in the skill, the gymnast's shoulders were more open during the supported performance, and her legs were again straighter. This will be due to the length and effort in the skill being increased in comparison with the unsupported skill.

Touch-down: Both the shoulders and hips were slightly more closed during this phase in the unsupported skill, and legs were much straighter. This suggested that the gymnast was pre-empting the landing more in the supported performance, which was a positive response.

Push-off: During this phase, the gymnast's hips remained more open during the supported performance. This suggested that she had prolonged the snap-down

action and achieved more rotation in the first phase of the skill through good technique. Her arms were also straighter at this point than during an unsupported performance.

Landing: On landing, the shoulders of the gymnast were more closed, and the hips were more open. From the video, the supported backward handspring had a long first phase and a short second phase, which is in agreement with more open hips and closed shoulders as this is the resultant position of a dynamic second phase. During the unsupported performance the first and second phases had similar displacements.

Performance parameters: Gymnast 5 executed a slightly higher, but much longer performance over the training aid than on her own. She also sat lower and further back in her takeoff during the supported performance, making it an all-round better performance.

9.5.5 Conclusion of findings

Overall it has been shown to be possible to perform a good backward handspring over the training aid. Although some of the gymnasts involved in the study did not perform the two skills identically, there was enough evidence to show that mechanically they would have been capable of doing so in most cases. It is believed that if given adequate time to practise on the training aid more similar performances would be observed. This was however not possible as it would take several weeks of practice, and only one prototype training aid was manufactured, and so could not be provided to the various gymnastics clubs for a trial period.

In most cases certain techniques were actually improved in the supported performances: for example better takeoff positions, more open shoulders and hips in flight, even the transformation from loopy to long dynamic performances were observed.

The training aid was not designed for the use of gymnasts capable of already performing the skill, and so some differences in techniques used were always expected due to the unusual environment in which the gymnasts were required to perform.

9.5.6 Gymnast and coach feedback

Feedback was obtained from both the coaches and the gymnast present during the data collection. The answers were then collected and compiled and will be discussed below (Figure 9.2). Comments and suggestions from this data compilation will be used when considering what modifications need to be made to the training aid before the final assessments take place.

Gymnast feedback

The feedback received from the gymnasts was collated and graphed:

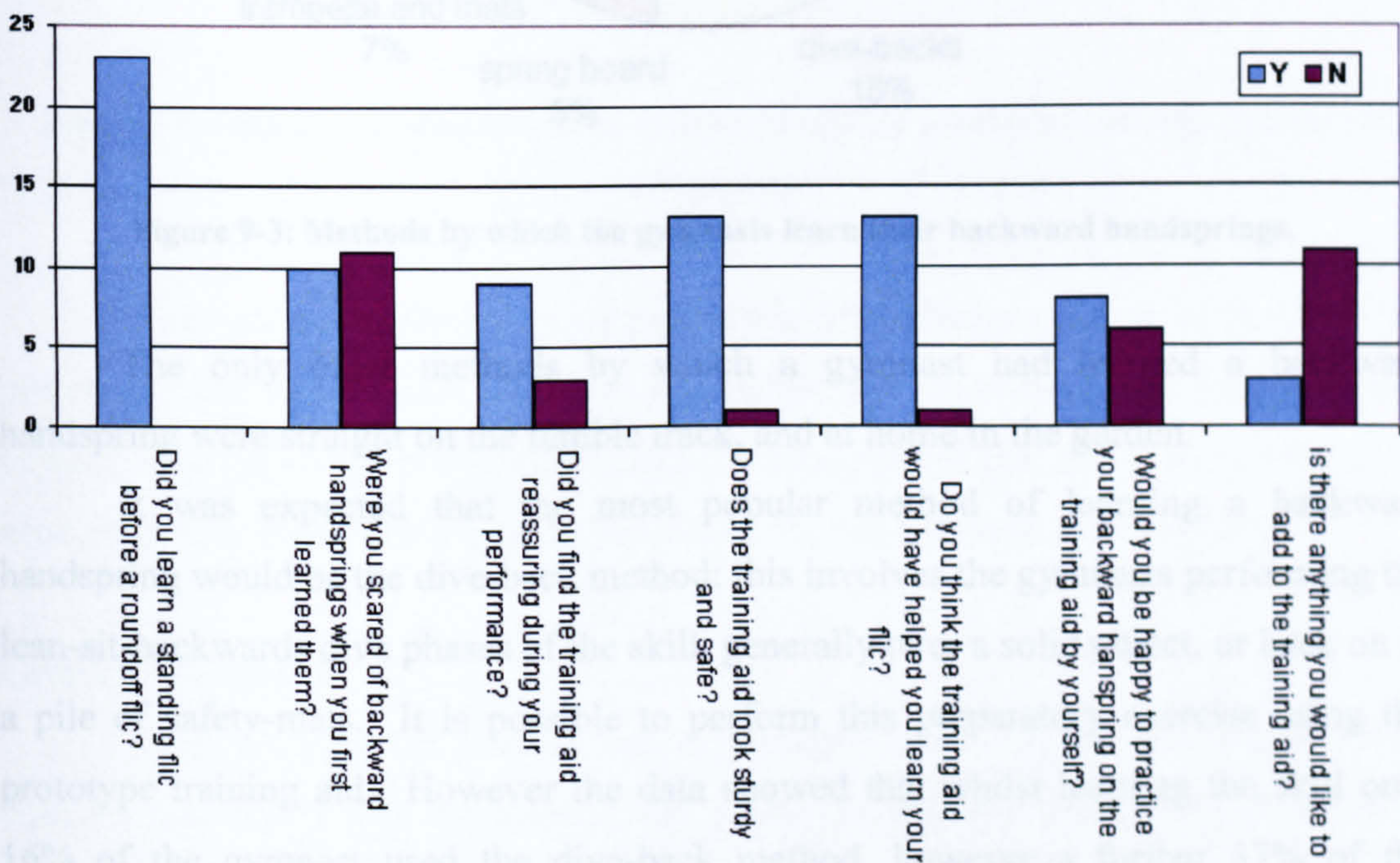


Figure 9-2: Results of gymnasts' feedback.

As can be seen in Figure 9.2, there was very positive feedback about the training aid from the gymnasts present at the data collection. Comments made included one gymnast who thought that the sit was too low, a couple of gymnasts were worried that they may hit the training aid, or that the overhanging mat may come off. Initially some gymnasts commented that they would be anxious of using the training aid alone, but after having support for a while, would feel comfortable using it without a coach.

The feedback established that a training aid for a standing backward handspring would be of definite use in a gymnasium as 100% of gymnasts present had learnt a standing backward handspring before the sequence of the round-off backward handspring series (Figure 9.3).

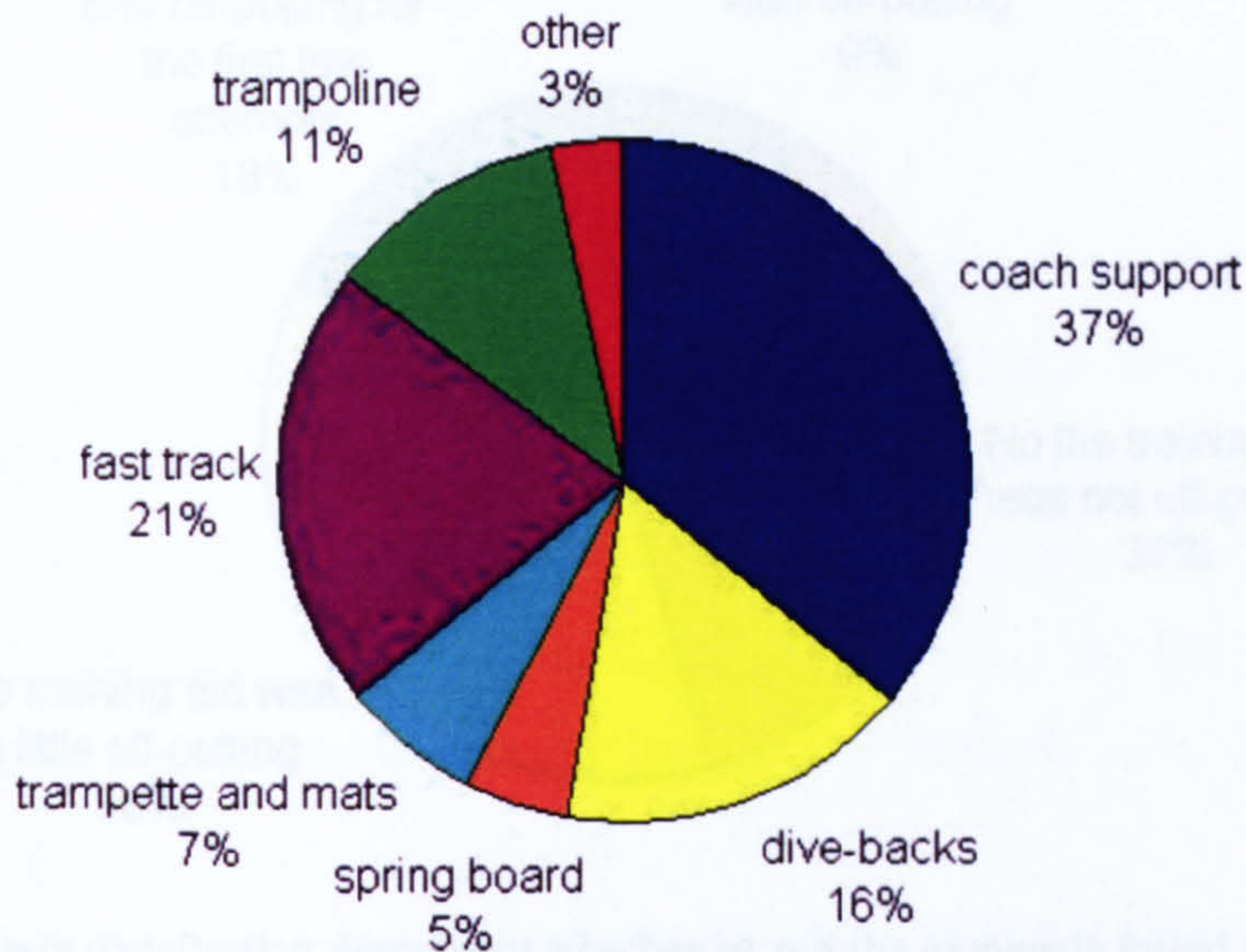


Figure 9-3: Methods by which the gymnasts learn their backward handsprings.

The only other methods by which a gymnast had learned a backward handspring were straight on the tumble track, and at home in the garden.

It was expected that the most popular method of learning a backward handspring would be the dive-back method: this involves the gymnasts performing the lean-sit-backwards dive phases of the skill, generally over a solid object, or back on to a pile of safety-mats. It is possible to perform this preparatory exercise using the prototype training aid. However the data showed that whilst learning the skill only 16% of the gymnast used the dive-back method, however a further 37% of the gymnasts were supported by a coach when learning the skill. During the learning phases of a backward handspring, when supported by a coach, the gymnast will have performed dive-back exercises into the coaches' arms in order to learn the orientation of the skill. In agreement with this, data from the coaches' feedback detailed that one of the preparatory exercises which the coach taught was "the gymnast dives back over my shoulder".

It was found that the main reason for the training aid being off-putting was that the foam seat was too low, creating too large a drop for the sit (Figure 9.4).

9.3.7 Design modifications

Through the testing and analysis which took place, it became apparent that the skills being performed did not follow precisely the initial orientation (as performed from the first data collection (detailed in Chapter 3) which was used to design the training aid. This was thought to be due to the data set from which the initial

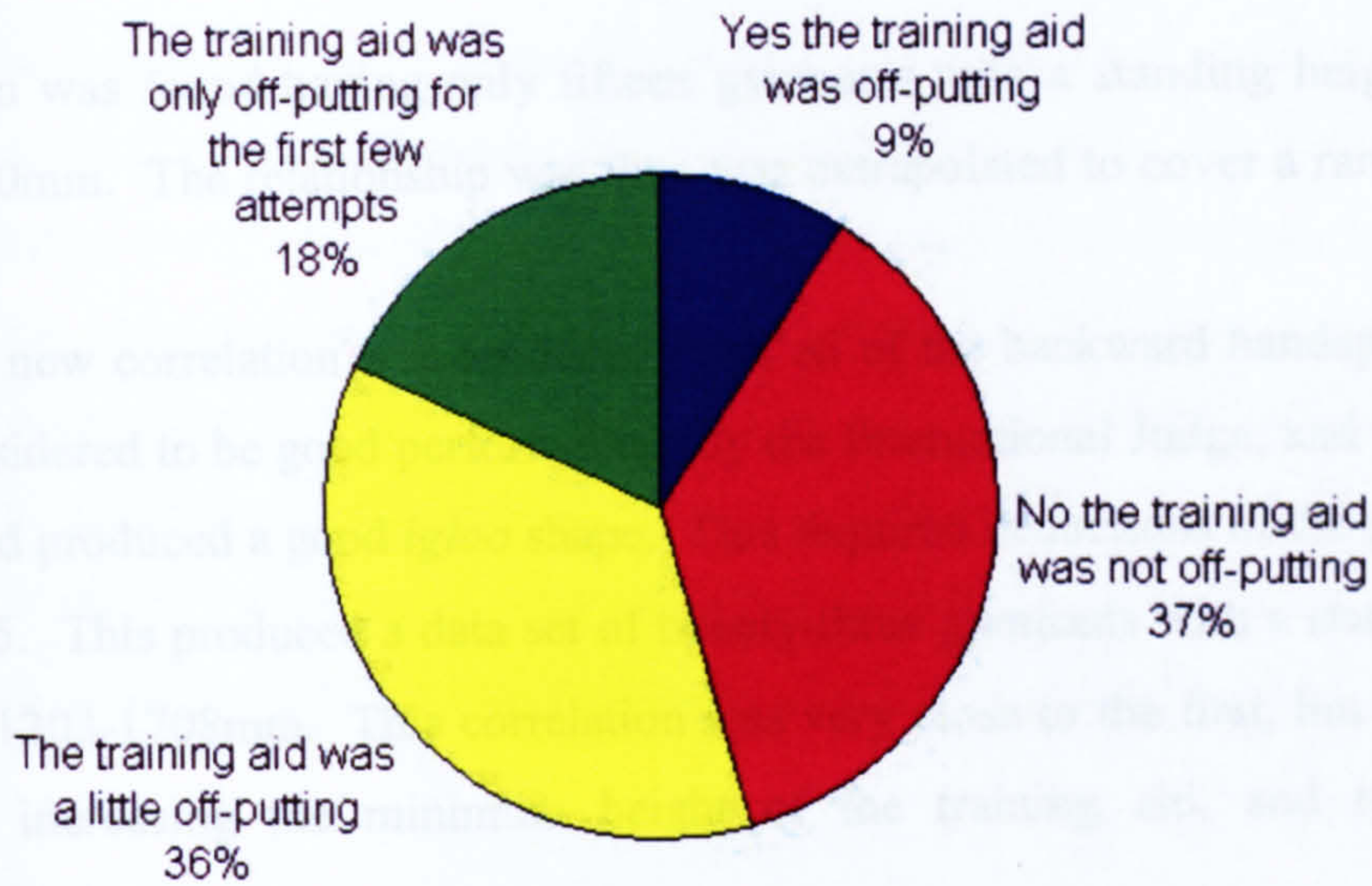


Figure 9-4: Data distribution describing whether or not the gymnasts found the training aid off-putting.

This will be carefully considered when final changes are to be made to the prototype. As can be seen above in Figure 9.4 the majority of the gymnasts who performed a backward handspring using the training aid did not find it off-putting, especially after being given time to familiarise themselves with the apparatus.

Coaches' Feedback

Feedback from the coaches was extremely positive. It was the opinion of all coaches questioned that the training aid would be suitable for the initial stages of learning a backward handspring, and they thought that in general the training aid would have helped their gymnasts learn the skill.

The feedback provided by the training aid in terms of the gymnast making contact with the training aid during the performance of a technically poor skill was deemed useful by both coach and gymnast. Coaches seemed happy to let gymnasts practice the exercises on the training aid alone while waiting turns for supported performance with the coach.

9.5.7 Design modifications

Through the testing and analysis which took place, it became apparent that the skills being performed did not follow precisely the initial correlation line produced from the first data collection (detailed in Chapter 7) which was used to design the training aid. This was thought to be due to the data set from which the initial

correlation was found having only fifteen gymnasts with a standing height range of 1203-1440mm. The relationship was then extrapolated to cover a range of 1100-1700mm.

A new correlation was produced from all of the backward handsprings which were considered to be good performances by the International Judge, and which when strobe-laid produced a good *igloo* shape. This required deductions of the performance to be ≤ 0.5 . This produced a data set of twenty-three gymnasts with a standing height range of 1203-1708mm. This correlation was very close to the first, but of a smaller gradient, increasing the minimum height of the training aid, and reducing the maximum height.

It was also decided that the training aid should have a more adjustable height so it could be more accurately tailored to the group of gymnasts using it. The training aid prototype had been manufactured with 100mm divisions on the upright post; it was decided to decrease these increments to 50mm.

Some of the gymnasts who performed the full skill over the training aid swung their arms back a lot during the *bend-extend* phase and consequently caught their arms on the over hanging mat. This mat was 1m wide on the prototype as it was an existing standard size mat. As this was a recognised technique, not a bad habit, it was decided that the mat should be made the same width as the top padded section (500mm) as originally designed.

The foam section on the top of the prototype training aid was produced from two pieces of foam. The bottom foam was dense protective foam, while the top foam was soft, spongy foam. Trials were carried out with the top section of foam not present, but gymnasts commented that the landings were not as comfortable, and so the extra foam will be present in the final design.

During constant use, the metal plate on which the foam section was attached bent to produce a very slight curve. The plate has been re-designed to be 7mm thick plate in the final design, instead of the original 3mm.

Initially, there were just three designed foam seats, of different heights, to be used with the three height settings. The seats were designed with 100mm size increments. It was found that 100mm increments gave too much of a variation between seat sizes. Consequently the seat sections have been re-designed to be comprised of four progressive sections of 67mm which build up on top of each other. The seating has been made stackable for ease of manufacture and to prevent excess matting requiring storage when not in use.

The bottom section of the seat foam had a complex profile to enable it to sit on top of the metal structure beneath but flush with the floor. This greatly increased manufacturing costs, especially when it was necessary to be cut into the bottom of each section. It was therefore decided that in addition to the foam seat a 50mm firm mat would be added as a floor section to the front and back of the training aid so that it was only necessary for this one section to involve the complex profile. The frame height was altered accordingly. This was for extra padding on impact of the hands on the far side of the training aid, and to reduce manufacturing costs.

9.6 Individual learning experience

Once modifications had been made to the training aid, the final stage of analysis was for a gymnast to learn their backward handspring using the training aid. For this two gymnasts were selected, one who could backward handspring on her own but with poor technique, and one who had not begun to learn the skill. Parental consent was obtained from both participants.

9.6.1 Skill improvement

Gymnast B was a nine year old club level gymnast who had self-taught herself a backward handspring before joining a gymnastics club. It was established by her coach that considerable work would be needed to correct the skill.

The first stage of this investigation was to establish the actual quality of the backward handspring, and to identify the weaknesses in the technique. The skill was performed on the tumble track at Loughborough University, and the performance was videoed with a standard 50Hz digital video camera. The performance was then judged by an International Judge, and comments were made on the weaknesses in the technique used.

The deductions taken from the performance were in excess of a whole mark. The skill was high and loopy, the gymnast let her knees travel forward during her takeoff, and she consequently brought her hands back under herself too close to her point of takeoff. This resulted in the centre of mass not moving far enough horizontally in flight and she collapsed from the handstand position on to her knees with her hands remaining in contact with the ground. The gymnast was identified as

needing to perform a lot of preparatory exercise work before reattempting the skill, and so this was to be performed on the training aid and when ready, the skill would be reassessed.

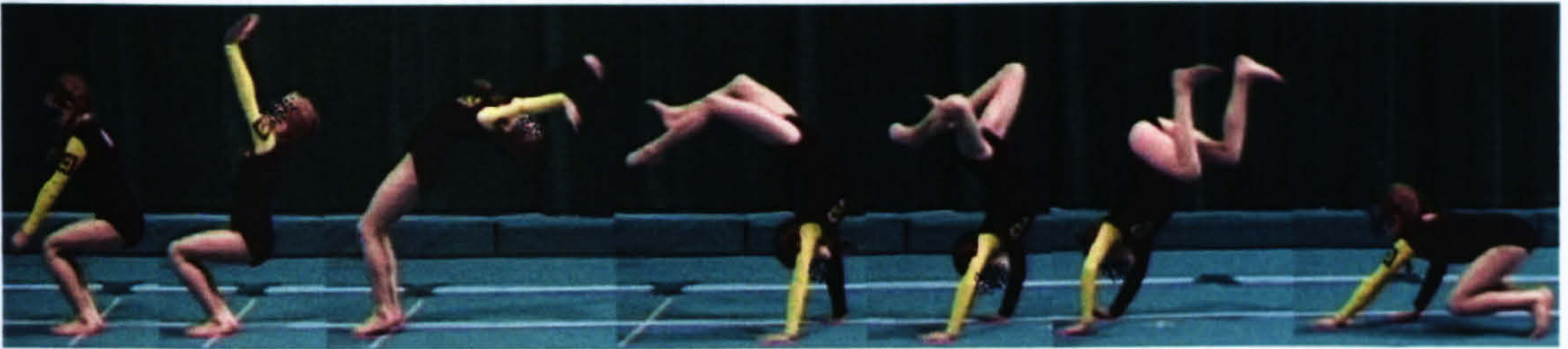


Figure 9-5: Gymnast B: Initial backward handspring.

Training Diary

Stage 1: Dive-backs – Completed stage in a single 15 minute session.

Stage 2: Dynamic dive-backs – Completed stage in six 20 minute sessions.

Stage 3: Supported backward handspring – Completed stage in eight 20 minute sessions. This was accompanied with shaping also on the floor.

Stage 4: Unsupported backward handspring – Completed stage in four 20 minute sessions.

Stage 5: Free Backward handspring – Completed stage in two 20 minute sessions.

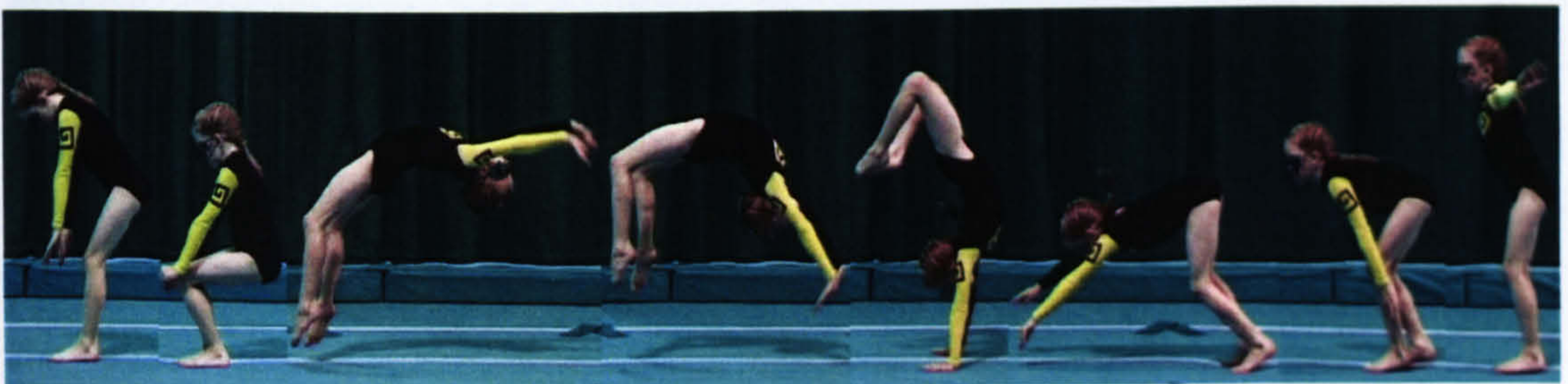


Figure 9-6: Gymnast B: Backward handspring after training.

The skill still needs work and still has a weak second phase, as can be seen in Figure 9.6. After less than seven hours training, which included time for the gymnast to accustom herself with the new training aid, the backward handspring has improved considerably. She no longer pushes her knees forward during takeoff, her takeoff direction and first flight have improved, and she is consequently now capable of landing the skill on her feet. It was the opinion of her coach, that it would have been unlikely that gymnast B would have made such considerable improvements with out

the use of the training aid, due to factors such as lower skill repetition, and less of the gymnasts skill attempts being ‘shaped’.

9.6.2 Skill learnt on the training aid

Gymnast O, was an eight year old regional level gymnast. She was at the stage in her training where she needed to learn a backward handspring, and volunteered for the study.

Training Diary

Stage 1: Dive-backs – Completed stage in a single 15 minute session.

Stage 2: Dynamic dive-backs – Completed stage in eight 20 minute sessions.

Stage 3: Supported backward handspring – Completed stage in ten 25-20 minute sessions, alongside repetitions on the floor with support.

Stage 4: Unsupported backward handspring – Completed stage in one 20 minute session. It was decided to coach the finer techniques of the skill on the fast track.

Stage 5: Free Backward handspring – Video was taken after two 20-30mins tumble session on fast track.

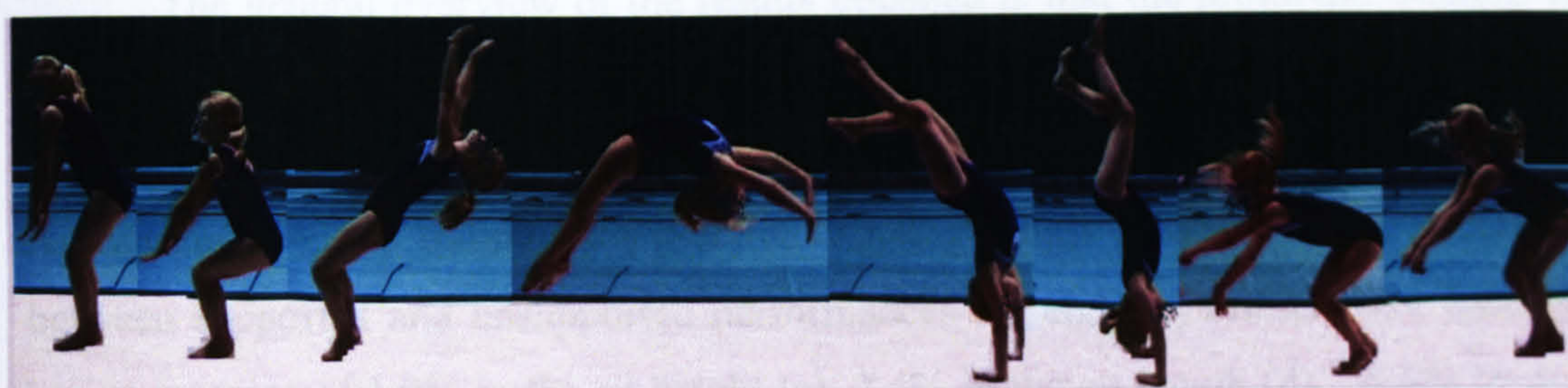


Figure 9-7: Backward handspring of gymnast O.

As can be seen in Figure 9.7, gymnast O has capably performed a backward handspring unsupported on the fast track. Prior to her training on the training aid only basic shaping had been performed within her training sessions, and she had only just begun to perform dive-back preparations. In less than seven and a half hours over a duration of three months, this gymnast was capable of performing a backward handspring. Although not perfect, she now has the understanding of the skill, and her coach intends to teach her the finer adjustments through repetition on the fast track.

When asked, her coach commented that it would generally take six to twelve months to reach this stage, depending on the frequency of gymnast training and group sizes.

9.7 Chapter summary

Chapter 9 much like Chapter 6 has investigated and discussed a variety of kinematic results. Joint angles, body configurations and overall joint displacements are a few of the factors which have been investigated. The prototype backward handspring training aid has been assessed with gymnasts of varying sizes and abilities and there has been very positive feedback from both the coaches and gymnasts involved. Modifications have since been made, and the prototype re-tested accordingly. The training aid was tested in accordance with British Standards, and has been shown to fulfil all of the requirements (Section 9.2.1). The training aid also underwent further safety testing which was specific to the conditions under which it would be used. 65-70kg masses were used during this testing and no permanent deformation or substantial movements were measured (Section 9.2.2). A multitude of simulated collision analyses were also performed (Section 9.2.3), and the training aid was seen to perform as designed, reducing the risk of injury during such collisions.

The general overview of the results obtained is that the prototype training aid has generally supported and aided gymnasts in learning the backward handspring (Section 9.6.2, gymnast O). It has been possible to perform a good standing backward handspring over the training aid (Section 9.5.4, gymnast 5) and average difference between supported and unsupported performances for eight gymnasts were found to be: an increase of 1.9% in the sit height (a), 2.4% in the sit length (d), 25.6% in skill length (g) and an increase of 22.9% in skill height (c). The training aid has also helped to correct common mistakes during the execution of a backward handspring (Section 9.6.1, gymnast B). The advantages of this training aid over all existing aids is that it allows a dynamic performance without support (Section 9.2.5, gymnast E, Section 9.6.1, gymnast B, and Section 9.2.1, gymnast O), and this was a fulfilment of the customer requirements (Chapter 3, Section 3.4.2).

10

Summary and Conclusion

10.1 *Introduction*

This chapter summarises the main findings of this study. Limitations of the procedures and methods used will be discussed, and suggestions for future improvements will also be recommended. Finally the potential of the training aids designed, the process via which they were designed, and how they can be adapted to wider use will be addressed.

10.2 *Summary of evidence*

By readdressing the objectives set in Chapter 1, information and knowledge gained throughout the study will be compiled and summarised in order to provide evidence that the objectives have been met:

Objective 1: To establish how the design of a training aid differs from that of a standard product.

The design of a training aid is considerably different from the design of other products, because it is crucial that the mechanisms used in learning a skill must be taken into consideration. For sports training aids this also requires considerations of the learning of the physical activity which an athlete is attempting to acquire.

From the literature reviewed in Section 2.4, Holding (1989) explains that there are two classifications of skill. 'Open' skills, require a good deal of interaction with external stimuli, whereas a 'closed' skill can be performed without reference to the environment. The acquisition of open skills is achieved through the use of concurrent feedback in a closed loop system. This is generally provided in the form of: visual, balance, or kinaesthetic cues from joints, tendons or muscles. In gymnastics, the information obtained through concurrent feedback guides the course of ongoing movements, for example visual information which helps a gymnast to maintain a balance skill. During the learning of these skills, the amount of practice is

a prominent factor in skill acquisition. Closed skills obtain information from the environment in which the skill is being performed. This is terminal knowledge, which occurs at the end of a movement. Feed-forward control using this information is used to guide the formulation of the next response (Holding, 1989). Examples of such terminal knowledge are: orientation of a landing, failure of a skill, or verbal feedback from the coach. A training aid developed to help teach a closed skill would therefore need to be capable of providing the user with some form of performance information to enable the acquisition of a technically correct skill. Training aids in general therefore are required to provide a safe environment in which the skill can be practiced whilst providing the user with performance information.

It is also necessary for the design of a training aid to incorporate a method of replicating the same environment as is experienced during the performance of the full unaided skill. This requires a detailed biomechanical analysis of the chosen skill to ensure that the training aid designed develops the correct motor learning requirements of the skill. A generic design methodology has been developed in Section 3.4.1.

Objective 2: To determine the fundamental requirements of a gymnastics training aid.

Through interviews and questionnaires answered by some of the most highly qualified gymnastics coaches in the UK (detailed in Chapter 3), and through the knowledge obtained from fulfilling the first objective, the fundamental requirements of a gymnastics training aid have been determined. The training aid should:

- Provide shaping and support for the crucial or chosen component of the skill.
- Not obstruct the movement of a good performance.
- Provide some form of feedback to the gymnast.
- Build confidence, strength and understanding of the skill.
- Encourage good techniques and help correct common mistakes.
- Lead to the unsupported performance of the skill.
- Where possible alleviate the requirement for a coach.
- Alleviate the anxiety of the skill, and build confidence and understanding of the skill.
- Where possible simplify the learning process.
- Be suitable for a range of gymnasts.
- Be quick and easy to used, therefore not increasing repetition time between gymnasts.

- Be safe to use, preventing foreseeable injuries from occurring.

A generic design path for the development of a gymnastics training aid can be seen in Section 3.4, Figure 3.22 and Figure 3.23 (a, b, and c), pages 57-60.

Objective 3: To establish what criteria may be used to identify a gymnastics skill for which a training aid may be designed.

From a survey conducted among nationwide International and High Performance Coaches, and elite senior gymnasts (as detailed in Chapter 3), and from information obtained through observations of various elite level gymnastics training sessions, criteria to identify a suitable gymnastics skill for which a training aid could be designed were established.

It was found necessary for the skill to be one of the most commonly taught skills, to be highly dependent on coach support and time, and to require the most repetition or training time. If the skill is critical to the development of an elite gymnast, and is favourable to the market demand (the coaches), then it will also be suitable for training aid design due to the amount of interest the equipment will receive. It may even be the case for such skills that existing, training aids or equipment setups have been established, and therefore the designed training aid must be developed to out-perform the existing equipment.

It was established that there are two main categories of gymnastics activities: balance skills and dynamic skills. The physical requirements of balance and dynamic activities vary greatly, and hence generally so do the skill acquisition processes (Figure 2.5, page 28). To ensure therefore that the study was applicable to a range of gymnastics skills, two contrasting gymnastics skills of those identified as suitable were studied: the handstand on rings, which 100% of Male Artistic coaches wanted, and the backward handspring, which 89% of the High Performance coaches wanted (page 33 and 34).

Objective 4: To determine the biomechanics of the selected skill and to establish what other considerations must be taken into account in order for a suitable training aid to be designed.

To understand the biomechanics of the selected skills the theoretical, scientific, and coaching literature were reviewed, preliminary investigations of the skills were performed in order to gain more understanding, and a theoretical-mathematical

description of each skill was developed in order to evaluate what parameters affected them.

Rings handstand: Using a two segment model of a handstand on a frictionless surface, the theoretical solution for control of the equation of motion of the handstand on the rings resulted in the same type of control strategy as was detailed in Yeadon and Trewartha (2003), for a one segment model of a handstand on the floor (Equation 11, page 74): $T(t) = pX_1(t - t_0) + d\dot{X}_1(t - t_0)$, (if T is based on a displacement X_1 and a velocity \dot{X}_1 at an earlier time). The main difference between the two control strategies was that the induced torque which controls the balance was produced at the wrist in the Yeadon and Trewartha (2003) floor model, but it was produced at the shoulder in the rings model discussed in this thesis (Chapter 4).

When sustaining balance during a floor handstand, the point of contact (hands on the floor) cannot move, and therefore it must be the mass centre which moves to regain position over the base of support to maintain balance. During a rings handstand, however, the mass centre moves a relatively small amount, and so it is the point of contact (the hands on the rings) which must move back and forth beneath the mass centre to maintain balance. To ensure that the training aid designed closely replicated the same environment as is experienced on the rings, multiple degrees of frictionless movement (as is available on the rings) had to be available to the gymnast to permit him to control the balance correctly.

Backward handspring: The backward handspring is a dynamic skill which has five main biomechanical phases (Chapter 7):

1. Backwards fall to get the centre of mass behind the point of balance.
2. 'Bend and extend', jumping backward and upwards into the air.
3. First flight, from the feet to the hands.
4. Impact on the hands, the subsequent pivoting about hands, and the arch to dish kip-action to generate second flight phase.
5. Second flight, from hands to feet, and landing.

The considerations which must be taken into account during the design of a training aid to help teach the backward handspring were found to be: the height and the depth of the sitting action of the backward handspring (performance parameters a and d , Figure 7.13, page 199), and the height and length of the 'arc' of the backward dive of the first phase of the skill (performance parameters c and g , Figure 7.13, page 199). No significant differences were found between the genders, or between

disciplines, and no significant trends were found for a relationship between any of the performance parameters and gymnast flexibility.

***Objective 5:** To determine the functional requirements of the gymnastics training aid for the selected skill, and whether the designed training aid incorporates these elements.*

The functional requirements of the gymnastics skills were established through an experimental biomechanical evaluation of each skill. The results of these investigations were translated into technical characteristics, and incorporated into the design of the training aids.

Rings handstand: From the research carried out in Chapter 4, the fundamental requirements of a training aid for the rings handstand were to closely replicate the control and technique used on the rings, but to also make the skill easier to perform on the training aid (customer requirements, Chapter 3, Figure 3.24, page 63). This was achieved within the design by permitting six movement degrees of freedom (Figure 5.3, page 117), provided by ultra-low friction linear rails and bearings. The magnitudes of the lateral and sideways movements were measured (maximum travel back and forth = 244mm, and maximum travel sideways = 180mm, Figure 4.29 and 4.30, page 107) to ensure that sufficient space was available within the training aid to enable the gymnast to hold a balance. Rotation was necessary as the rings permitted this movement, and it was also requested by the interviewed coaches. The design permitted the progressive learning of the skill by developing a progressive five stage training program (page 139) during which various restricted movements were released.

Backward handspring: From the research performed, the main functional requirements for a training aid for a backward handspring were to support the gymnast in the first phase of the skill but not to obstruct a good performance (customer requirements, Chapter 3, Figure 3.25, page 64). The training aid needed to be fully adjustable to suit different shapes and sizes of gymnasts, in order to be capable of supporting a range of users for the purpose of shaping the skill and reducing the risk of injuries. This was assessed by measuring the established performance parameters of 15 backward handsprings deemed 'good' by an International Judge. From these measurements correlation relationships were established (Table 7.2, page 204), and from these, the training aid dimensions were calculated (Table 8.3, page 210). The safety and usability of the training aid was assessed by overlaying video of backward

handsprings over an image of the training aid (Section 9.2.1, 9.2.2, 9.2.3, page 238-244). From this analysis and from practical trials detailed in Chapter 9, the adjustable features of the training aid also permitted a range of gymnasts to execute good performances of the skill without obstruction. The training aid was designed using positional performance data (Table 7.1, page 203) to ensure that it would not obstruct a good performance, and was adjustable in height, and depth.

The training aid also needed to provide the gymnast with feedback, which would permit the gymnast to efficiently perform repetitions alone. The design was developed so that collisions between the gymnast and the training aid during normal use would not result in injury (Section 9.2.3, page 243), and a procedure of normal use was developed (page 247). Also the design incorporated suitable structures and materials in order make the training aid as safe as possible. These were established through various mechanical stress calculations (Chapter 8, page 217-218, and 224-227).

***Objective 6:** To design, build and evaluate a prototype training aid to help in the learning of the selected skill.*

Biomechanical analysis of the two training aids, together with elite coach and gymnast feedback has lead to the conclusion that the training aids do assist the learning of the backward handspring, and of the handstand on rings.

Rings handstand: The rings handstand trainer has been shown to utilise the same control technique as was demonstrated on the rings. Through the analysis of Vicon displacement data, the prototype training aid was measured to have the most similar magnitudes of displacement to the rings out of all the training aids assessed (prototype - 3mm up and down, 68mm back and forth, 71mm side to side; rings – 0.5mm up and down, 172mm back and forth (some swing present) and 91mm side to side; Section 6.6.6, page 174). EMG data showed that for the majority of muscles measured, the prototype training aid produces the most similar data to the data obtained from the rings trial, especially with respect to the wrist muscles, where during all trials except for the prototype training aid (with all degrees of freedom released) and the rings, the wrists were being used to help control the balance, whereas on the rings and prototype training aid only muscle tremor was observed (Table 6.10, Table 6.11, Figure 6.16 and Figure 6.17, page 166-170). Finally the force data collected on the prototype training aid was measured to be of a smaller magnitude than that measured on the rings (prototype - $F_x = 57.6\text{N}$, $F_y = 23.1\text{N}$; rings - $F_x =$

77.5N, $F_y = 31.4\text{N}$, Table 6.12, page 171), the training aid was expected to have much lower forces due to the low friction rails rather than cables which inherently involve a horizontal component of the tension.

The progressive learning stages of the training aid have also been shown to develop the required control process, and as more degrees of freedom were released, the measurements taken on the prototype training aid became more similar to the measurements taken on the rings (Figure 6.16, Table 6.12, Table 6.13, and Table 6.14, pages 167-183).

Feedback has indicated that the rings trainer has simplified the rings handstand, whilst retaining the required techniques, and it has been quoted as being 'simple but brilliant' by technical members of British Gymnastics.

Backward handspring: From data taken during performances of backward handspring over the prototype training aid, it has been shown that 8/8 of the participant gymnasts were capable of performing their standard 'good' technique with the training aid set at the correct height (Table 9.5 and Table 9.8).

The backward handspring training aid has been used to teach a gymnast the skill (Section 9.6.2), and to correct the poor technique of a different gymnast (Section 9.6.1) and it has been observed to be successful in both instances. Gymnast feedback has been very positive (Figure 9.2, page 244), with only 9% of the gymnasts involved in the assessment being put-off by the training aid (Figure 9.4, page 246). Coach specific feedback was extremely positive. It was the opinion of all coaches involved in the assessment that the training aid was suitable to help in the learning of a backward handspring, and that they were confident that it would help their gymnasts learn the skill (page 261).

Research Question: *What is involved in the learning of gymnastics activities, and if training aids can assist in skill acquisition, how can scientific knowledge of these activities be used to underpin the design and development of these training aids?*

This research question has been addressed through the completion of the six objectives above. A study was first carried out to establish what is involved in the learning of a skill, what made a skill suitable for training aid design, and furthermore, which skills this requirement encompassed. There are two classifications of skill: 'open' skills, which require a good deal of interaction with external stimuli, and 'closed' skill, which can be performed without reference to the environment. The acquisition of open skills is achieved through the use of concurrent feedback in a

closed loop system, whereas closed skills obtain information from the environment in which the skill is being performed (feed-forward). Further study into design processes, skill acquisition, and biomechanical data collections led to the development of a generic design path and design methodology for the development of gymnastics training aids.

By following the design methodology, from the skills identified as being suitable, two contrasting skills were then studied: theoretically with information obtained from reviewed literature, and practically through a biomechanical analysis. Existing training aids for both skills were analysed, and design flaws were identified. All of the aforementioned information obtained was then used to establish the technical requirements of the two training aids, and they were then designed and manufactured, to assist in the learning of the skills.

In order to assess how such training aids could assist in skill acquisition, and if the scientific knowledge used during the equipment development had been effective, further biomechanical analysis was undertaken. The two training aids were assessed differently. The rings training aid was analysed to establish if it utilised the same balance control as was observed on the rings, and it was compared to training aids which were developed with significantly less scientific input. The training aid successfully fulfilled its requirements, and also out-performed the existing training aids. The backward handspring training aid was assessed with various experienced gymnasts to ensure that it permitted a technically good performance without obstruction at a variety of heights, and it succeeded. A gymnast was taught the skill using the training aid, and a further gymnast corrected poor technique using the training aid. No comparisons were made between the prototype and the existing less scientific training aids, as during a preliminary assessment of these apparatus and from High Performance Coach feedback, they were all rejected as being unsuitable to teach the full dynamic skill.

In conclusion, through an in-depth biomechanical assessment of a gymnastics skill, it is possible to design a training aid which will positively affect the learning and acquisition of that skill. Such training aids will also be highly likely to out-perform existing non-scientific training aids for the same skill.

10.3 Limitations and progressive developments

Rings Handstand Trainer

As it stands, this piece of equipment is made from wood, steel and foam. For it to become viable to market, it must comply with the fire regulations of the British Standards. It has not been possible to test this specification due to the requirement of specialised test facilities. This is a limitation of the rings training aid to date. Also the linear guides used in the design of this piece of equipment are a significant expense; for this training aid to be more desirable to manufacturers other simple mechanisms may need to be considered and analysed, such as a limited-motion wheel configuration or a cheaper alternative to the existing linear guides. One further limitation to the study was the use of only one gymnast during the data collection. Although the training aid was tested by multiple elite male gymnasts, conclusive scientific evidence was produced from only one gymnast, and therefore further subject testing would further support the design of the training aid.

Backward Handspring Trainer

The backward handspring trainer has already been designed using existing gymnastics equipment components and has also be used to teach a gymnast to perform an unsupported backward handspring. The limitations of this study have been the number of gymnasts taught the skill using the training aid, therefore more testing would further support the design of the training aid. The progressive development for this particular training aid would be to advance to manufacturing status, and to produce a first fully-processed manufactured prototype. This would enable an investigation into any manufacturing complications or difficulties experienced, and permit alterations to the design accordingly.

10.4 Relevance and justification

As stated in section 10.2: *'The design of a training aid is considerably different from the design of other products, because it is crucial that the mechanisms used in learning a skill must be taken into consideration. For sports training aids this also requires considerations of the learning of the physical component of the activity which an athlete is attempting to obtain'*, and this has been proved through the use of scientific research. Two gymnastics training aids have been developed and shown to

aid in the learning of the corresponding skills, and have been proven to be more suitable than, and out-perform the existing training aids available for the two skills.

The methodology used to design the rings handstand training aid when considered in simple terms is a training aid for the progressive learning of a motor control skill. It would therefore be possible to easily adapt and use this methodology to design equipment for such projects as rehabilitation (for example balance or walking) , physio exercises, resistance training, or even robotic motion.

The backward handspring training aid when considered in simple terms, safely teaches the gymnast the correct body configuration and take-off velocity and direction to achieve a specified flight path. The simple adaptation of the methodology followed for the design of a backward handspring trainer could therefore easily be used for the design of long jump, high jump, ski jumping, martial arts or hurdle training devices.

The complete methodology described throughout this thesis is relevant in the context of the design of any sports apparatus, and ever further a field, the design of any object which is involved in a biomechanical activity, for example to assist an accident victim re-learn to walk.

10.5 Further research

The main capacity for further work in this field is to firstly assess the equipment over a longer period of time by having a large number of gymnasts use the training aids as part of their regular training. This would permit a more rounded assessment of the two training aids, but it would be necessary to collect such data over a number of years and for a significantly large number of gymnasts at different stages in their skill learning process.

Further work could also be carried out to investigate the manufacturing procedure of both of the training aids. Although both training aids have been designed to be completely viable for manufacture, further considerations into tooling and material costs, overheads, and initial manufacturing outlay costs would be needed in an attempt to get both training aids to a stage at which their manufacture would not only be suitable, but also profitable.

The other area in which further work could be carried out would be to use the design methodology described in this study to design a training aid for a different activity, whether it be sports orientated or not. Such work would certifiably confirm

the design methodology used throughout this study. Examples of training aids which could be designed via this process could be:

1. A training aid to help teach high jump: The training aid would need to establish the flight path and flight parameters of the skill, in order to produce a safe and adjustable object over which an athlete could train without the risks involved in landing on the high jump bar. A biomechanical analysis of the skill would be required to ensure that such a training aid would help the athlete and not hinder his or her natural style in any way. A training aid for this purpose would help the athlete to learn to jump, and help the athlete to improve the jump technique in a safe environment. It might therefore be composed of a padded object over which to jump, but also some form of safety padding on the opposing side of the new 'bar' to prevent injury during a poor exit from the jump.
2. A training aid to help teach a one-handed handstand to be performed on a single long-arm in a Acrobatic Gymnastics balancing skill: This skill will involve the *top* gymnast performing a one arm handstand, whilst balanced on the hand of a single straight arm of the *base* gymnast. The *top* gymnast will have to cope with perturbations due to both the limited shoulder stability of the arm of the *base* gymnast, and the movement of the *top's* own centre of mass during the skill. The balance is inherently unstable and requires a significant quantity of strength and skill. Such skills are learn progressively, and at present only pedestals are available on which the skill can be practised. A training aid for this skill would be required to incorporate the inherent 'wobbles' of the balance in order to permit the *top* gymnast to gain the required shoulder strength and balance control. This could be obtained via a mechanism such as an unbalanced rotating mass, or some other vibration device; however it must be located in an environment which is safe enough for the gymnast to perform the balance.
3. A training aid which attaches to the Asymmetric-bars to help condition the closing of the shoulder angle during a float upstart: This skill is crucial in the development of any gymnast who uses the Asymmetric-bars. It is a skill which requires specific timing and strength in order for it to be successfully achieved. It is a time consuming skill for

coaches, and although various conditioning exercises exist for the skill, they mostly require the gymnast to be on the bar and utilise assistance and support of the coach. Those exercises which are not performed on the bar, only help train small sections of the crucial action and can allow the gymnast to use muscles during the activity which they cannot use during the performance of the full skill: for example, using a trolley-trainer, the gymnast can push her back into the trolley in order to help her close her shoulder angle. The design of a training aid to condition this skill on the bars would have to incorporate a standard gymnastics bar, either as a component of the aid, or as a standard external piece of equipment that the training aid would need to 'fit' around.

For each of these examples the process described in this thesis may be used in the design and development of training aids for these skills.

10.6 Conclusion

People will always be required to learn new skills, and often this involves an aid of some description. In this study, a generic design methodology for the development of training aids has been proposed, and tested by means of its use. Gymnastics and skill specific adaptations of this methodology have been formulated throughout the study, a combination of which have lead to the production of two successful gymnastics training aids. The training aids have been analysed both mechanically and biomechanically, and comparisons have been made with existing training aids. Both of training aids designed within this project have been proven to assist in the learning of their respective gymnastics skills, and to be more suitable than, and out-perform, the existing respective training aids.

'Skill (noun)- (1) The ability to do something well, usually gained through experience and training; (2) - something such as an art or trade that requires training and experience to do well' (Encarta Dictionary, 2006). Learning a skill is a complex activity, and if it is possible to obtain scientific knowledge about a specific task, and then use this knowledge to design a suitable training aid, then learning will become a more efficient and more pleasurable task.

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Appendices

Appendix A - 3-Dimensional Model Drawings of the Training aids:

- Appendix A1 – Rings handstand page 301
- Appendix A2 – Backward handspring page 304

Appendix B – Full Requirement Trees:

- Appendix B1 – Rings handstand page 307
- Appendix B2 – Backward handspring page 310

Appendix C – Product Design Specifications:

- Appendix C1 – Rings handstand page 312
- Appendix C2 – Backward handspring page 316

Appendix D – Model of a handstand on a frictionless surface from Chapter 4:

- Appendix D1 – Full maths description from Chapter 4 page 321

Appendix E – Displacement data from Chapter 6:

- Appendix E1 – Rings handstand comparisons page 332

Appendix F – Correlation data for performance parameters from Chapter 7:

- Appendix F1 – Correlation graphs page 338

Appendix G – backward handspring data from Chapter 9:

- Appendix G1 – Backward handspring data page 343
- Appendix G2 – Discussion of data page 346

Appendix A

Full 3-Dimensional Model Drawings

Appendix A1 – Rings handstand

Appendix A2 – Backward handspring

Appendix A1 – Rings handstand

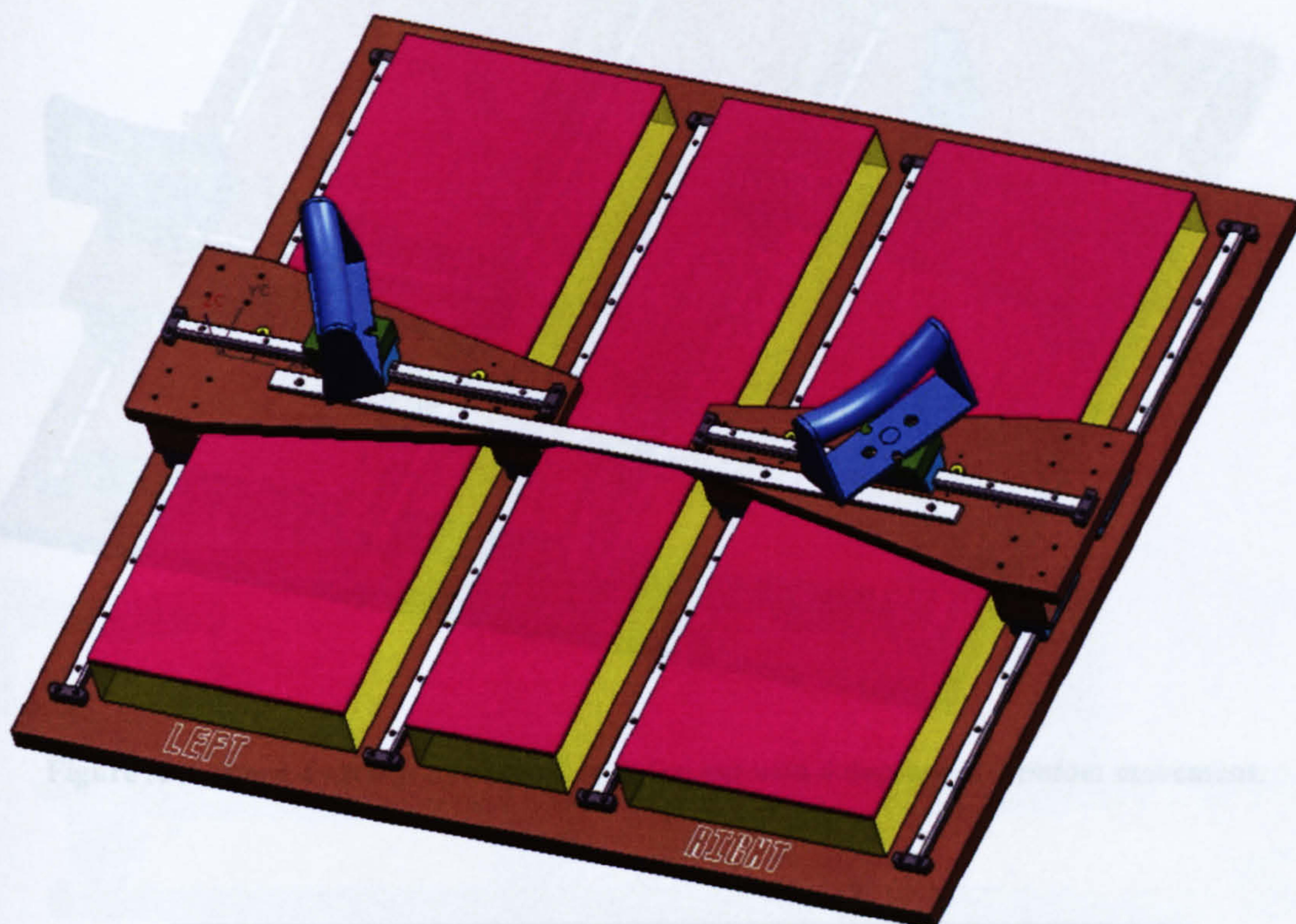


Figure A-1: Stage 1 - Rings handstand training aid only 1 degree of freedom.

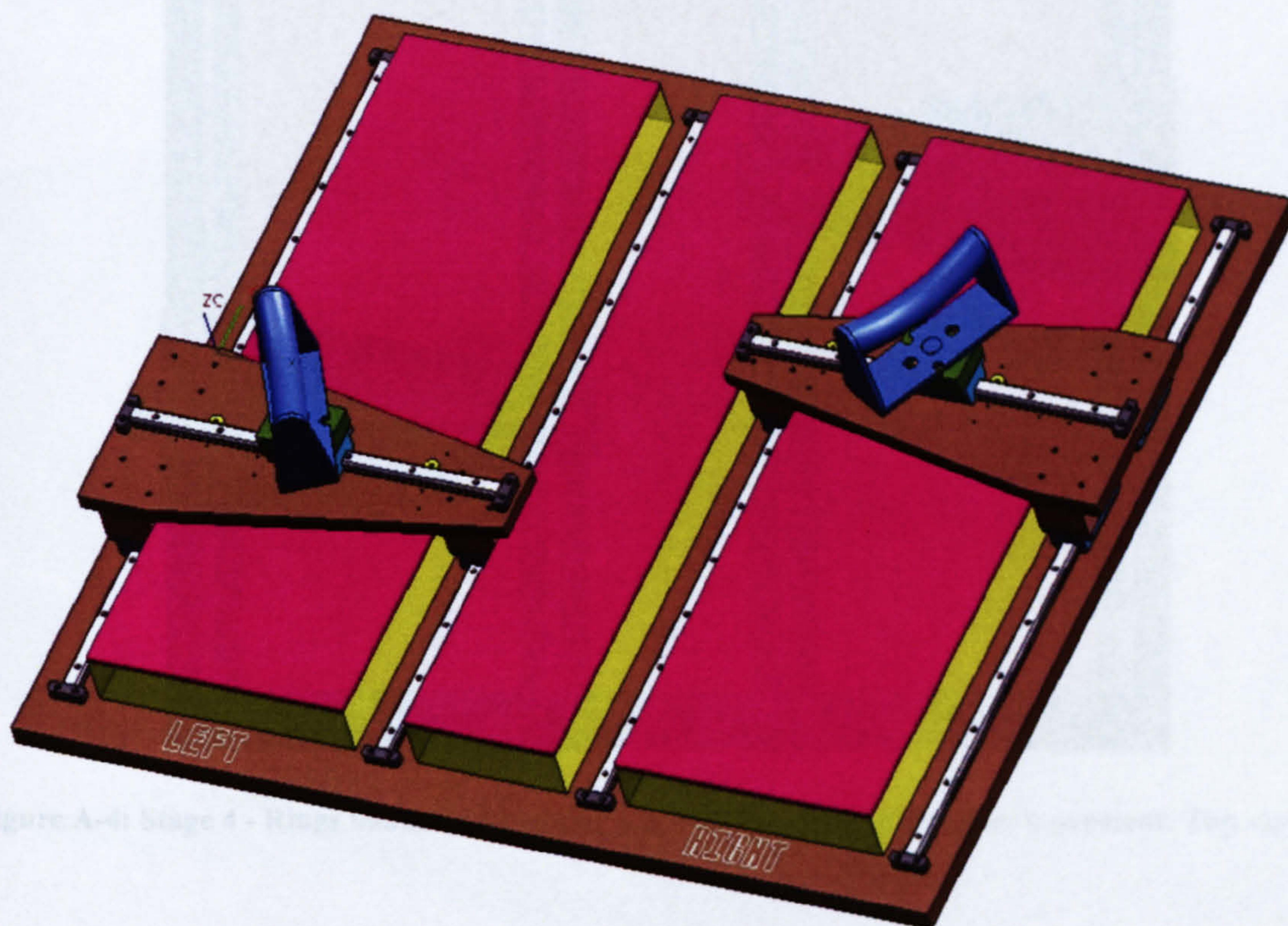


Figure A-2: Stage 3 - Rings handstand training aid with 4 degrees of freedom, with limited sideways movement.

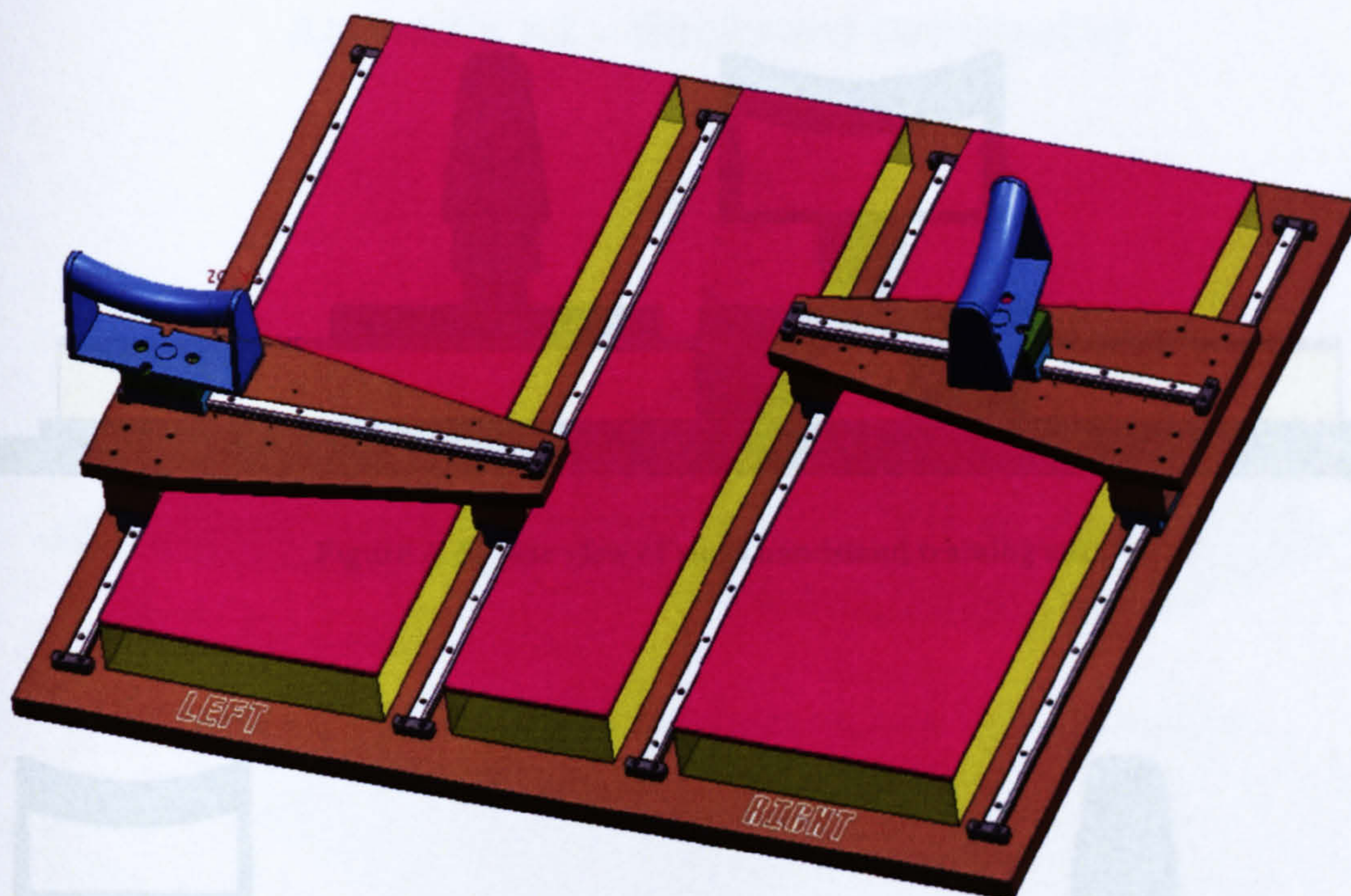


Figure A-3: Stage 4 - Rings handstand training aid with 6 degrees of freedom movement.

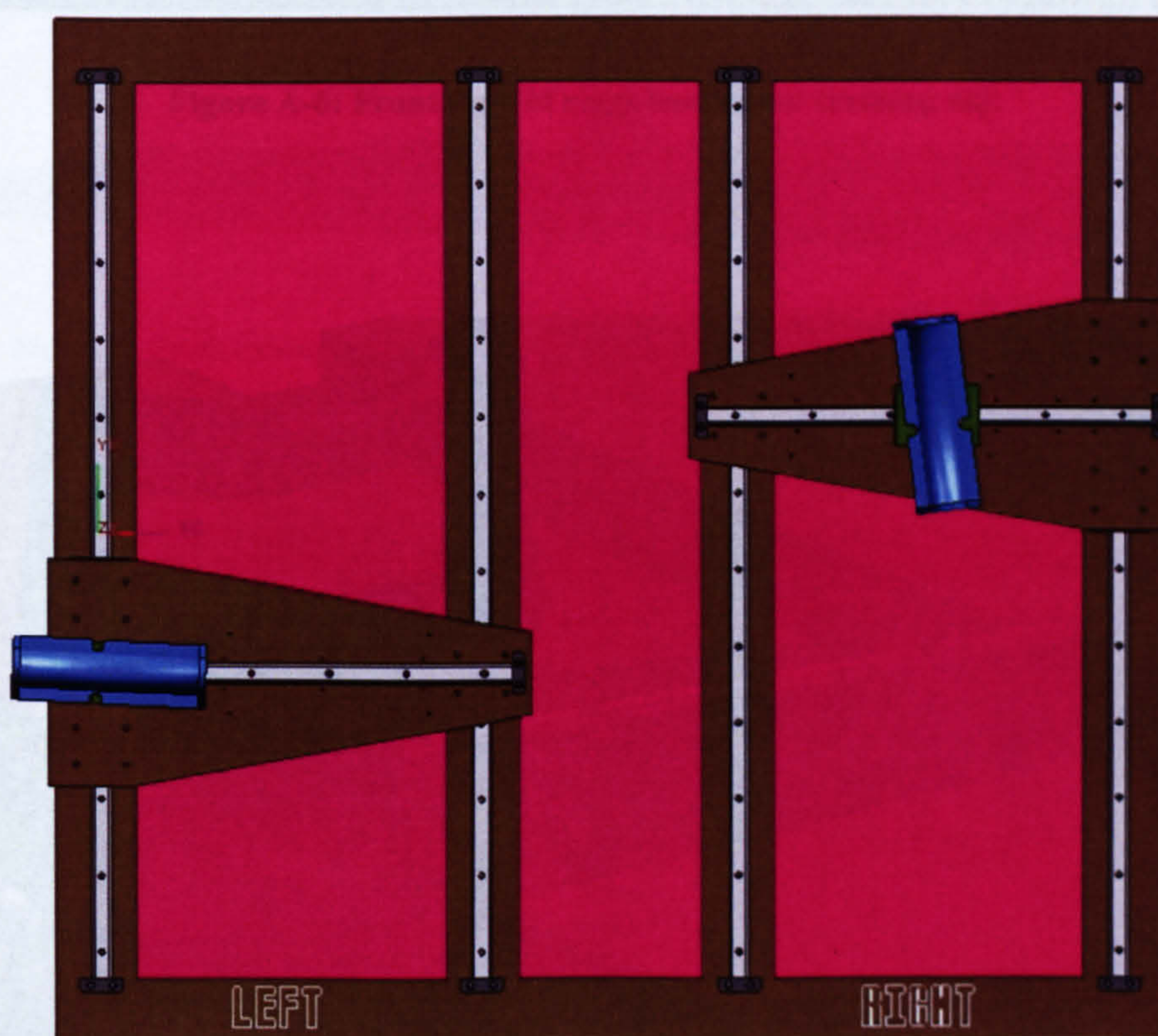


Figure A-4: Stage 4 - Rings handstand training aid with 6 degrees of freedom movement: Top view.

Figure A-7: Close-up of rings handstand training aid assembly.

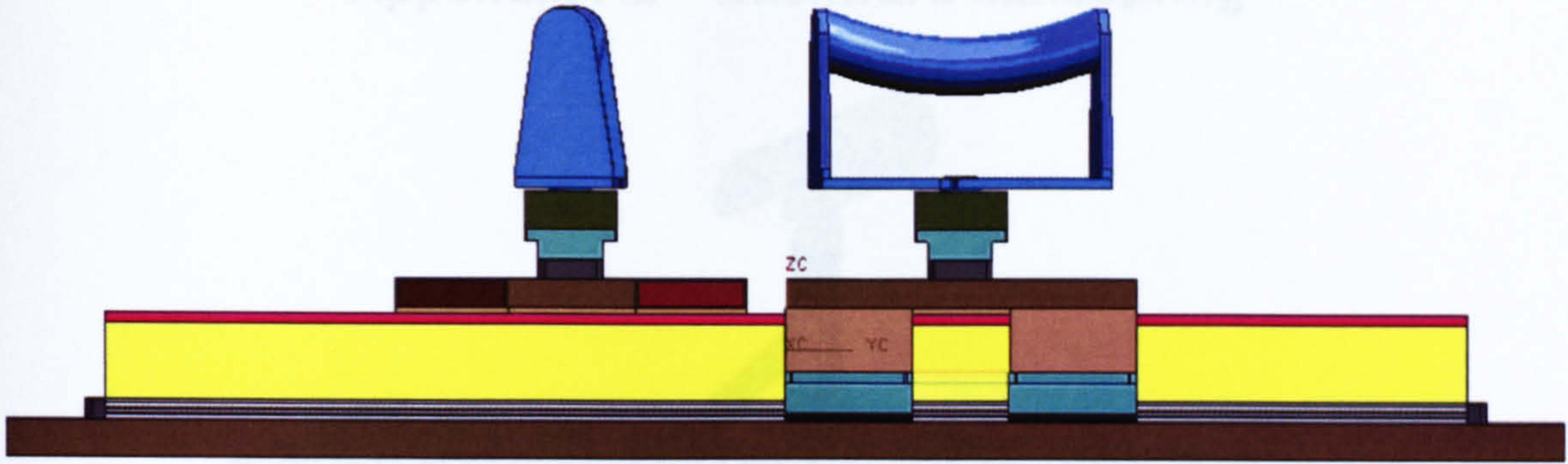


Figure A-5: Side view of rings handstand training aid.

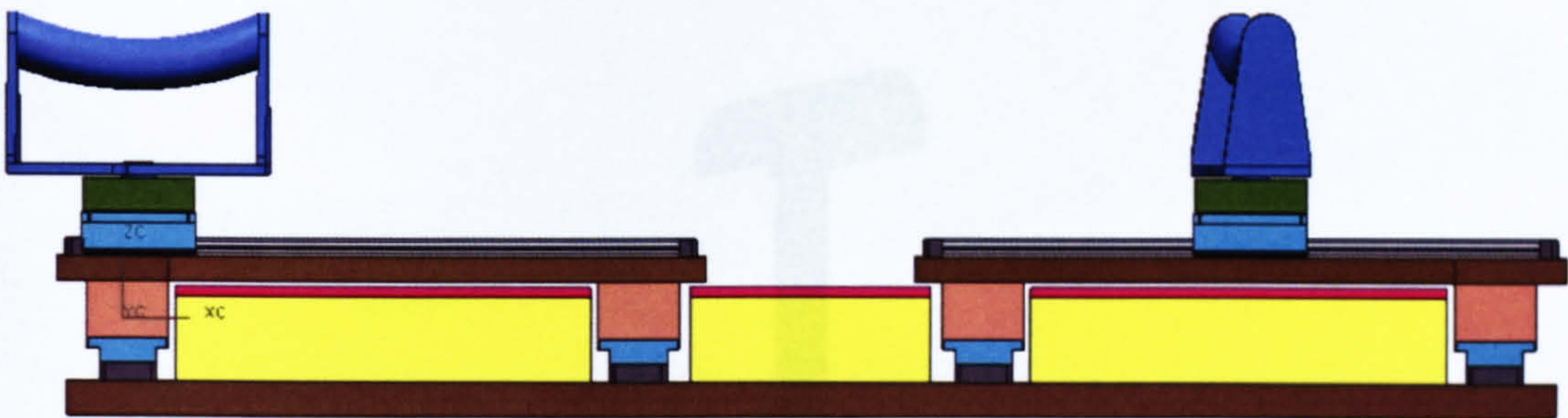


Figure A-6: Front view of rings handstand training aid.

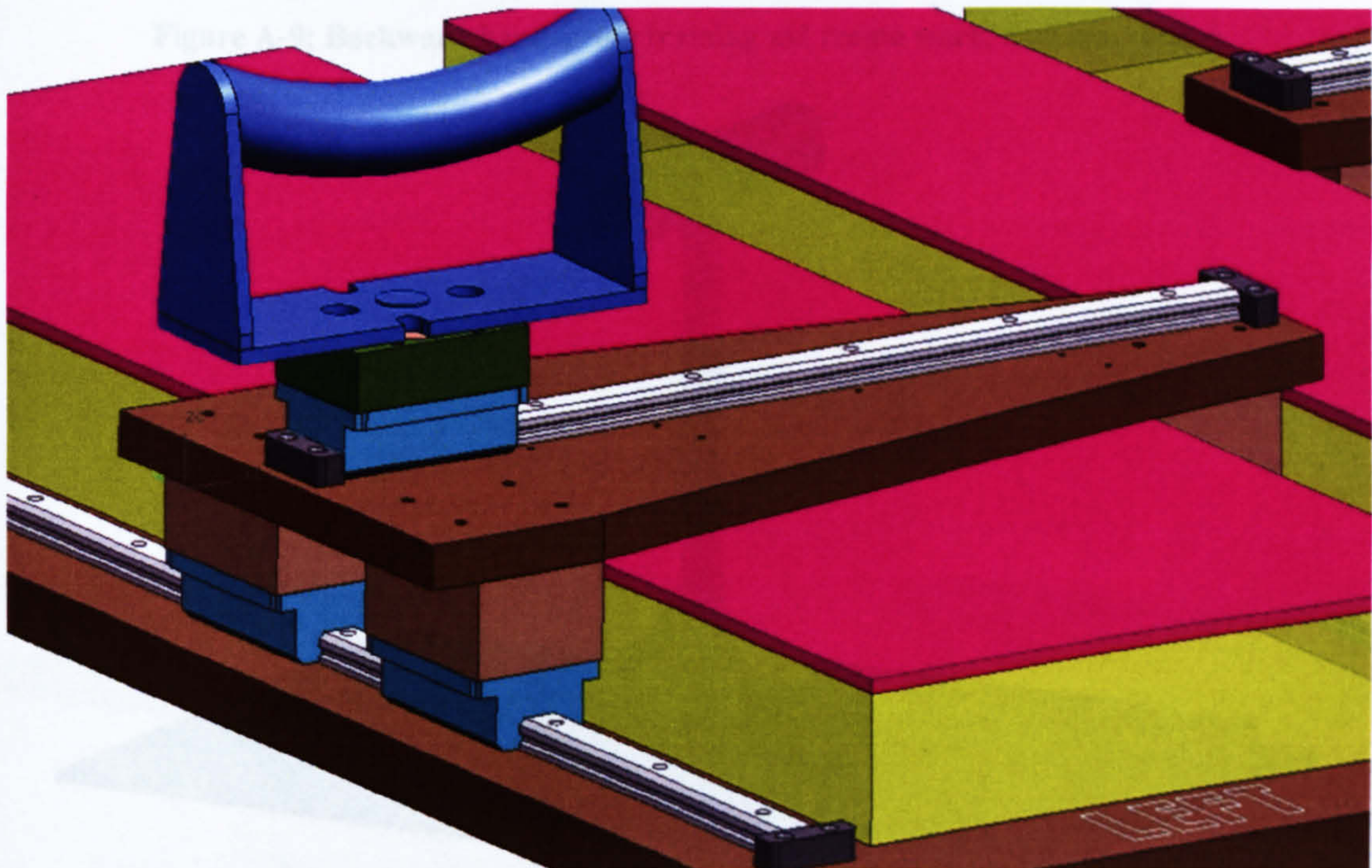


Figure A-7: Close-up of rings handstand training aid assembly.

Appendix A2 – Backward handspring

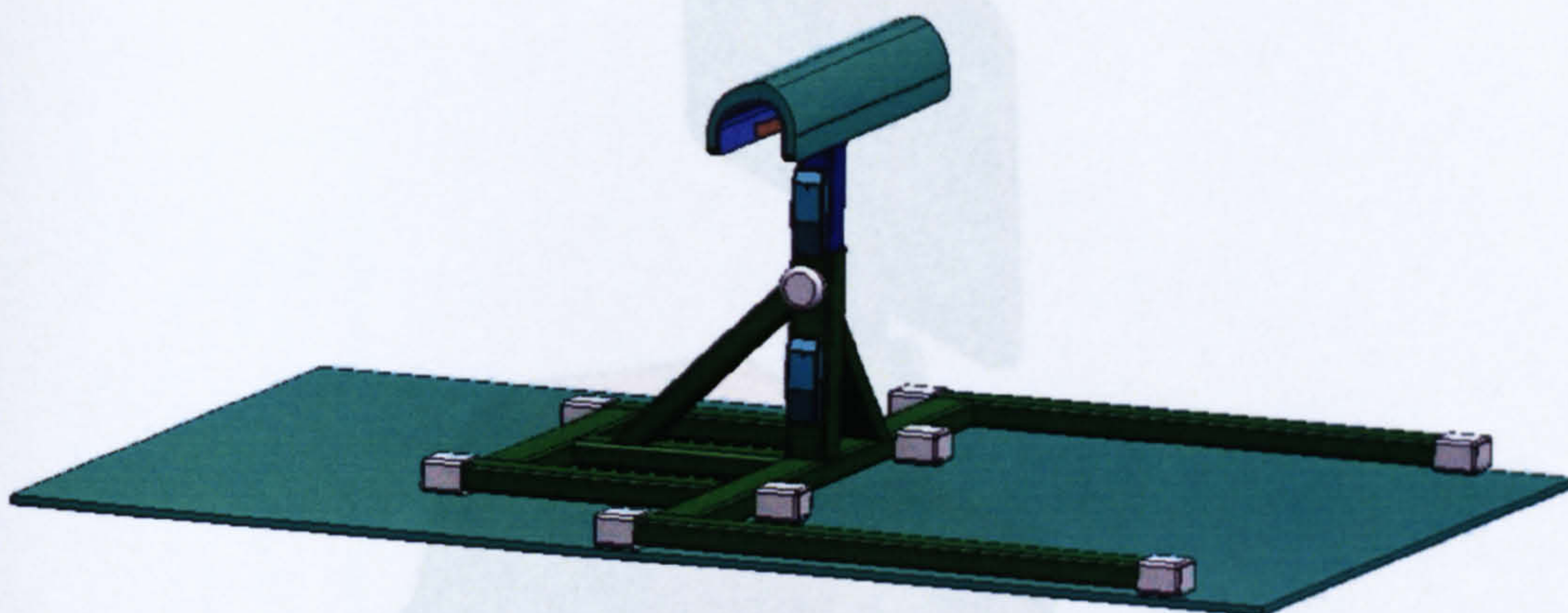


Figure A-8: Backward handspring training aid frame work: small setting.

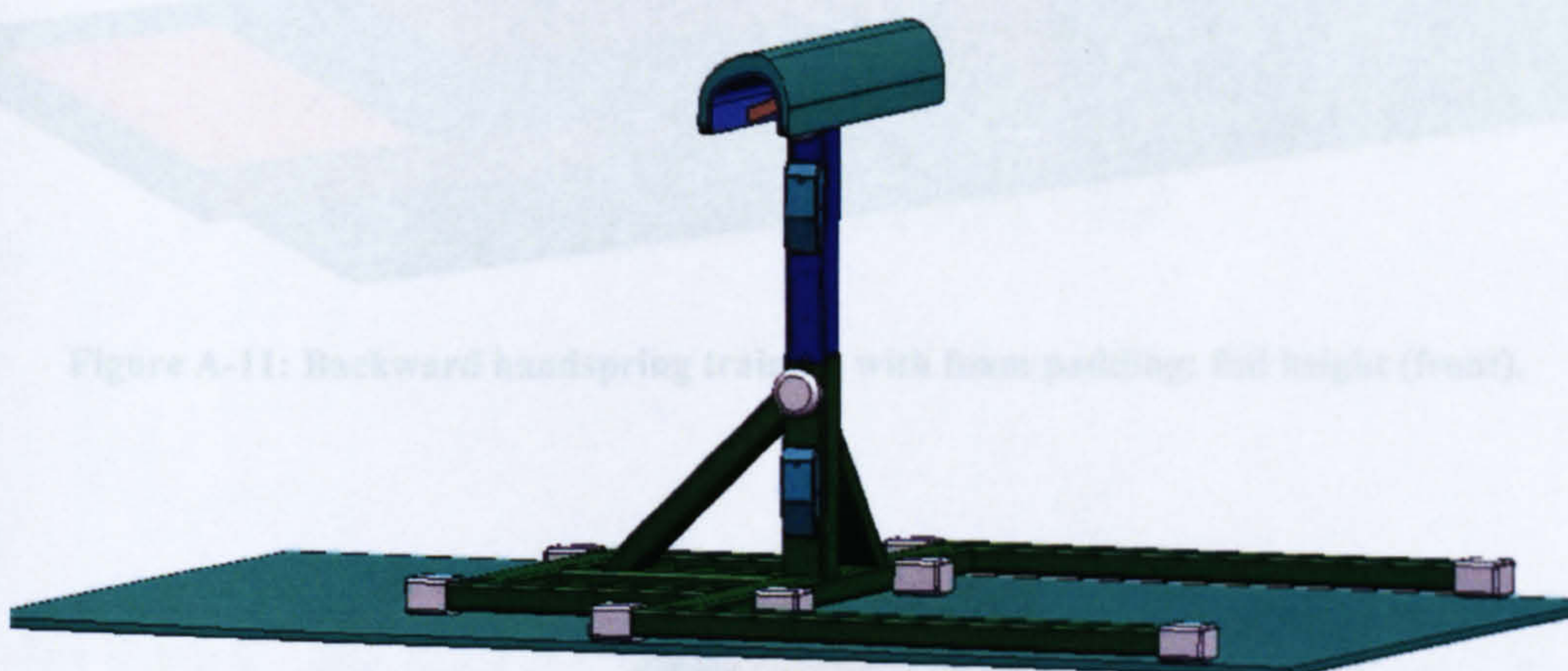


Figure A-9: Backward handspring training aid frame work: medium setting.

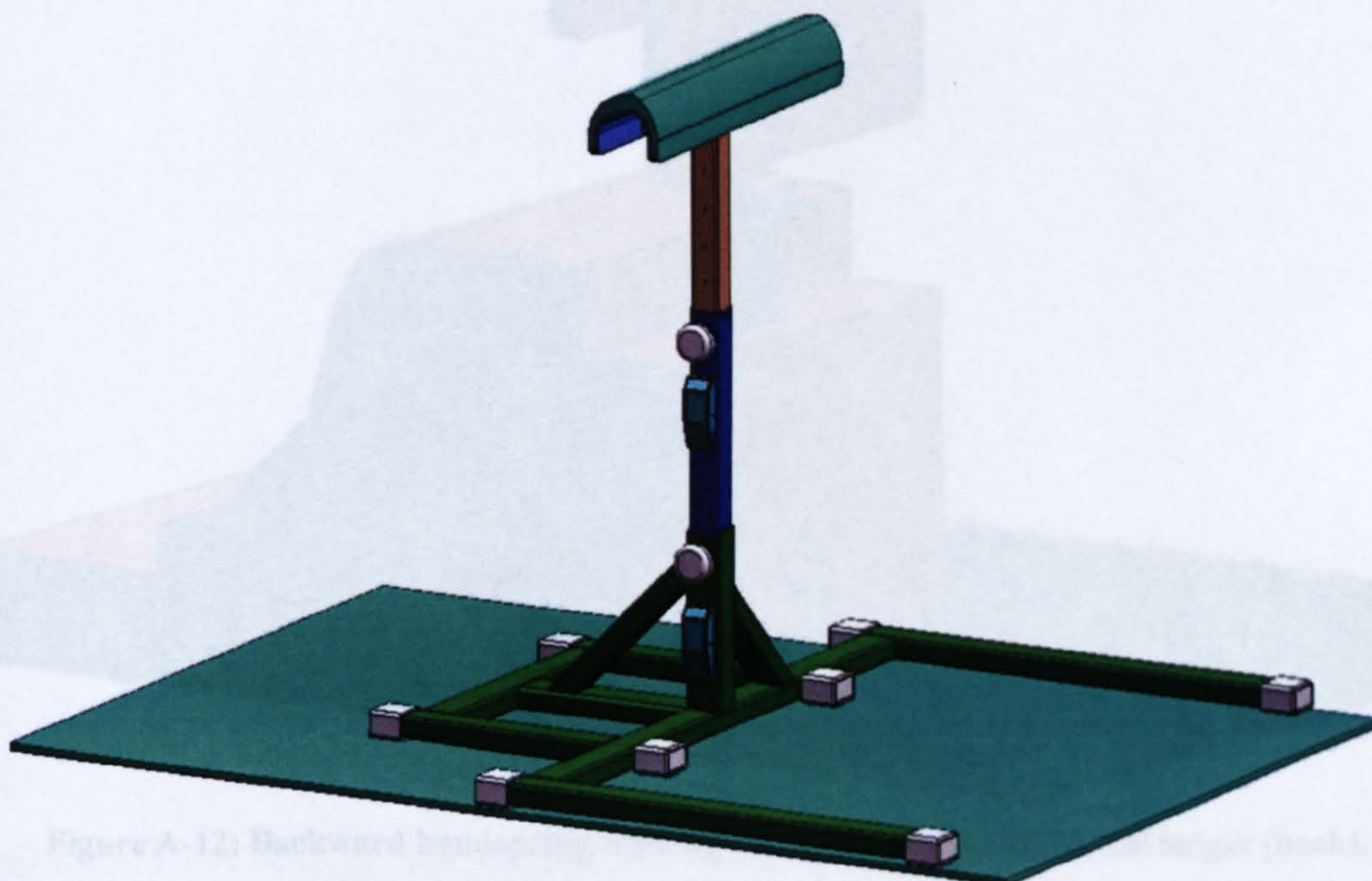


Figure A-10: Backward handspring training aid frame work: large setting.

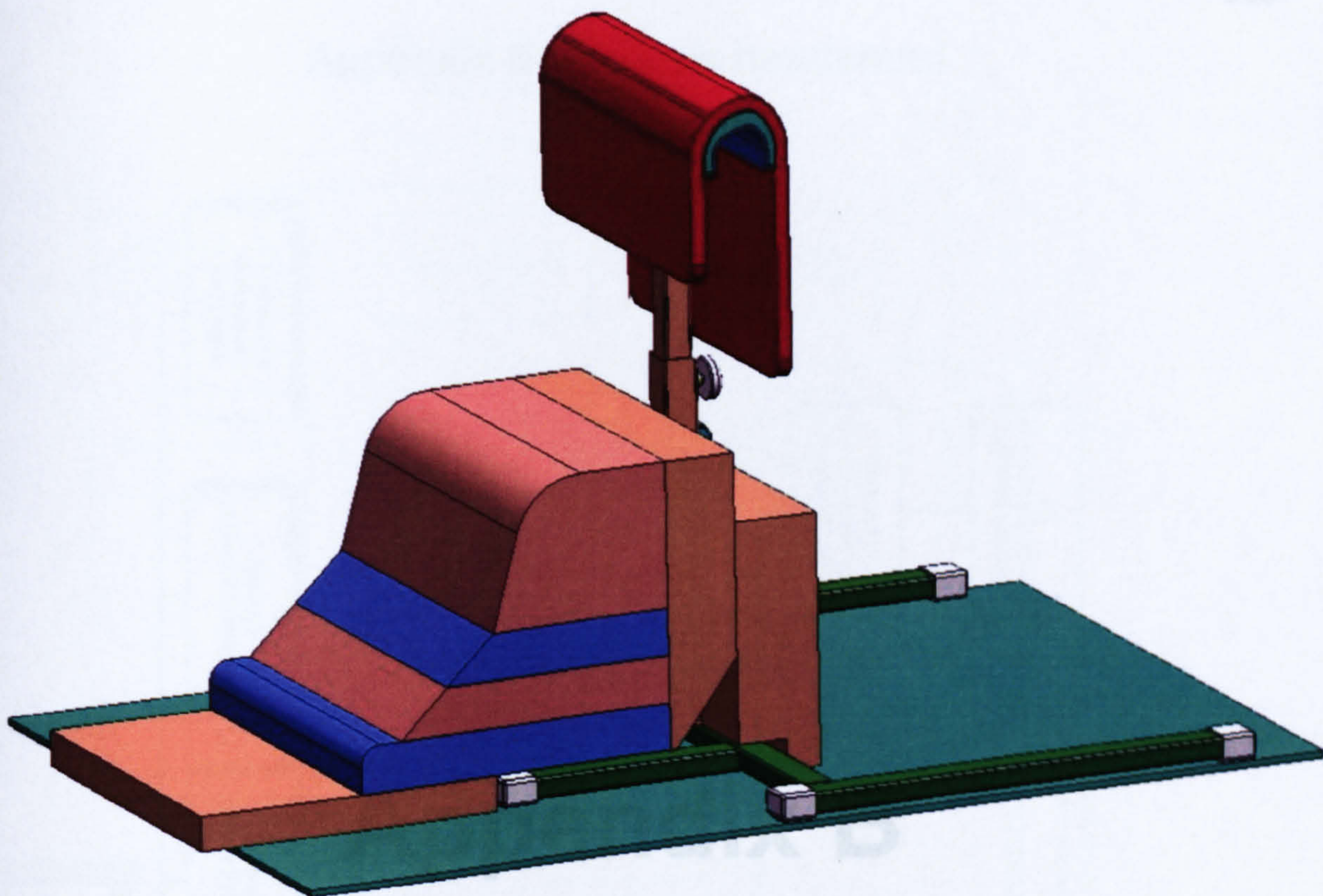


Figure A-11: Backward handspring training with foam padding: full height (front).

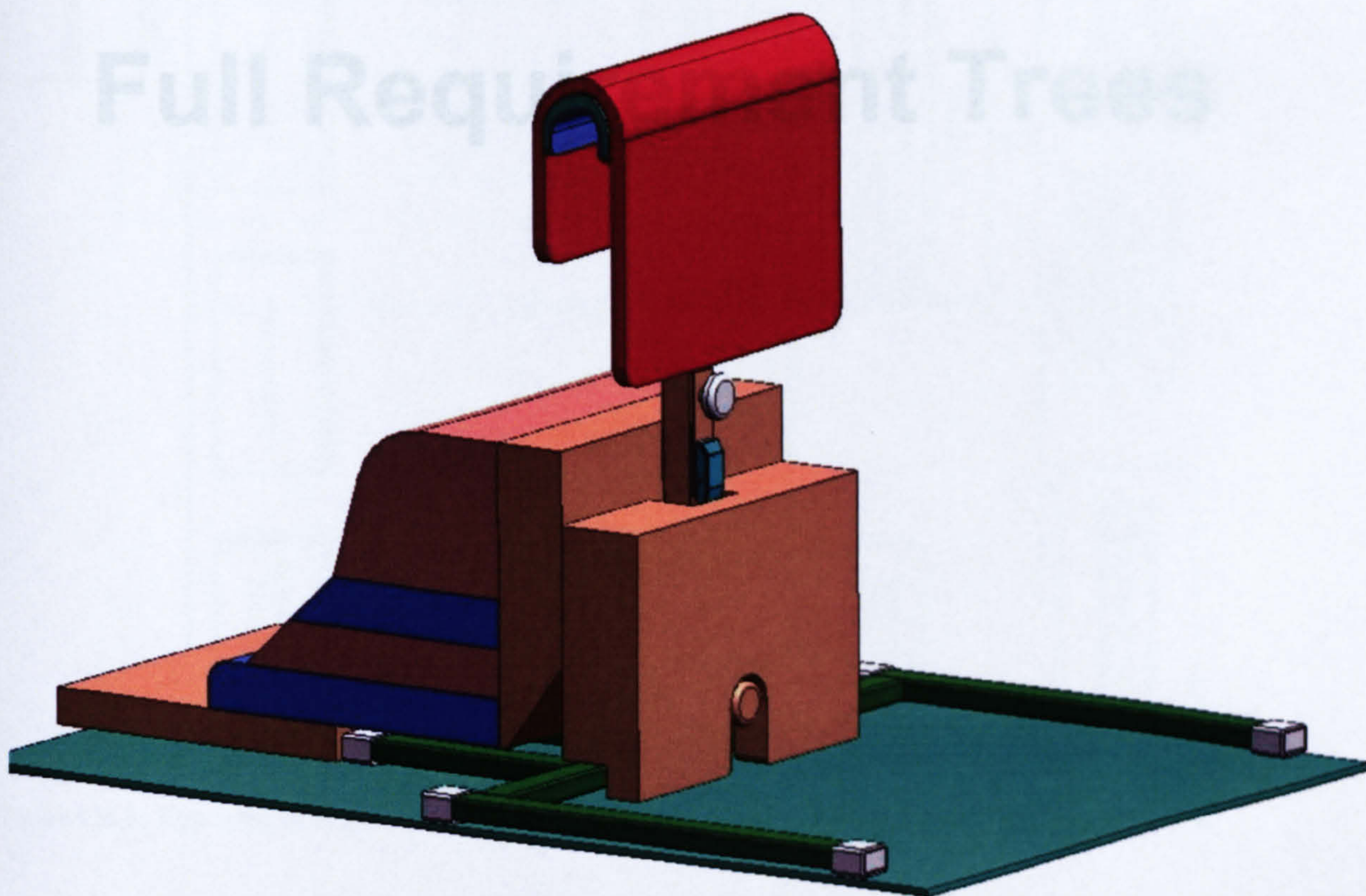


Figure A-12: Backward handspring training aid with foam padding: full height (back).

Appendix B

Full Requirement Trees

Appendix B1 – Rings handstand

Appendix B2 – Backward handspring

Appendix B1 – Rings handstand

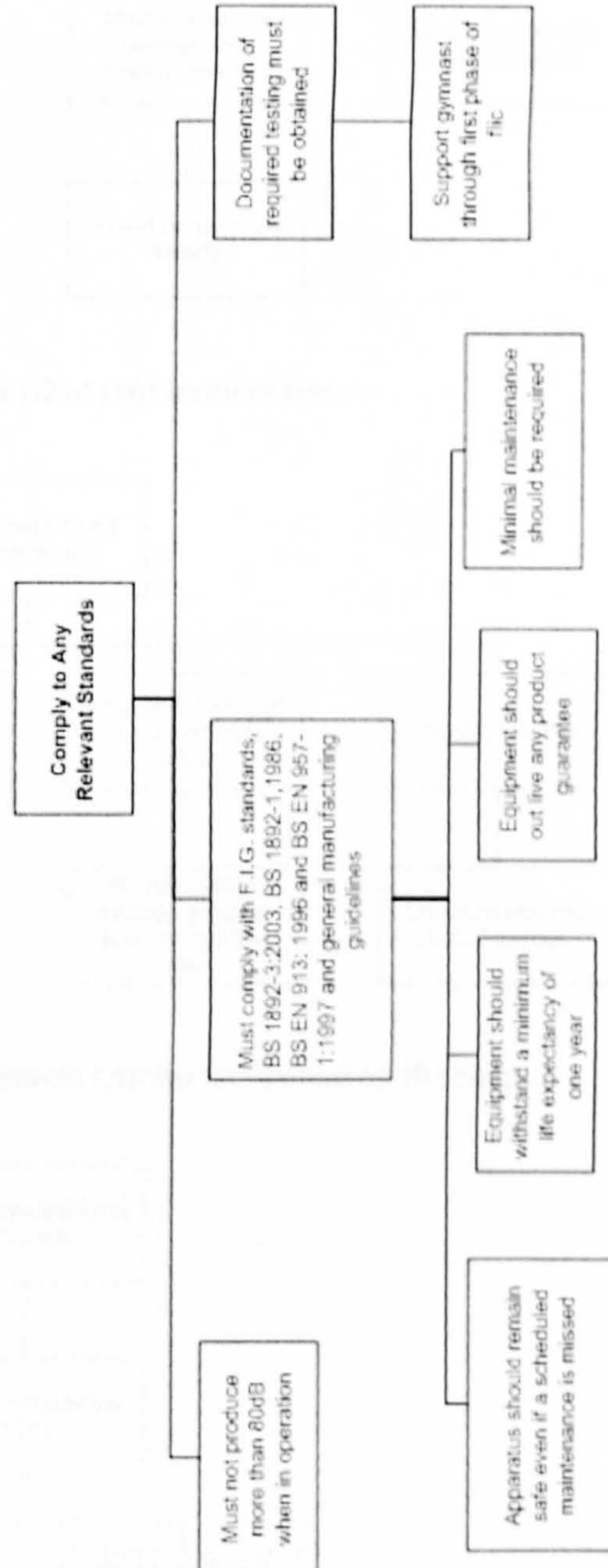
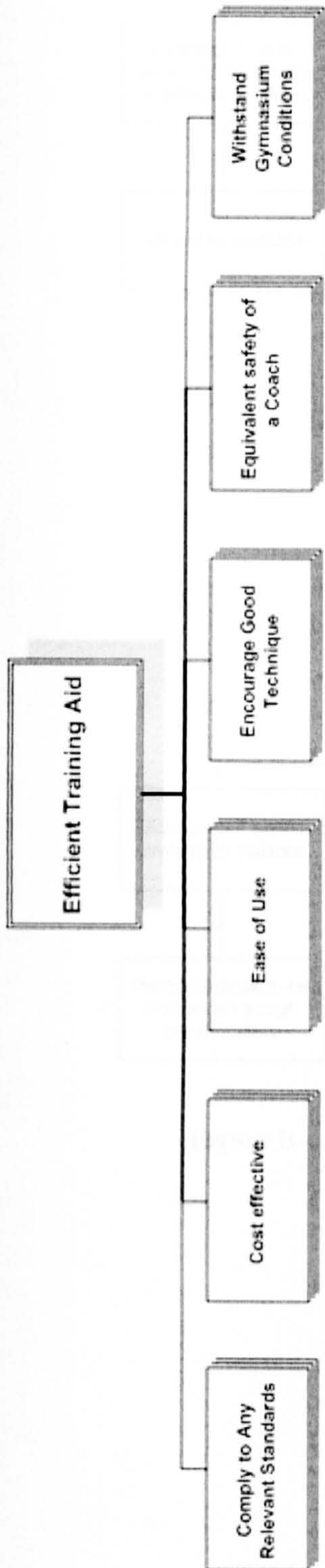


Figure B-1: Top level of requirement tree.

Figure B-2: Sub level 1.1 of requirement tree.

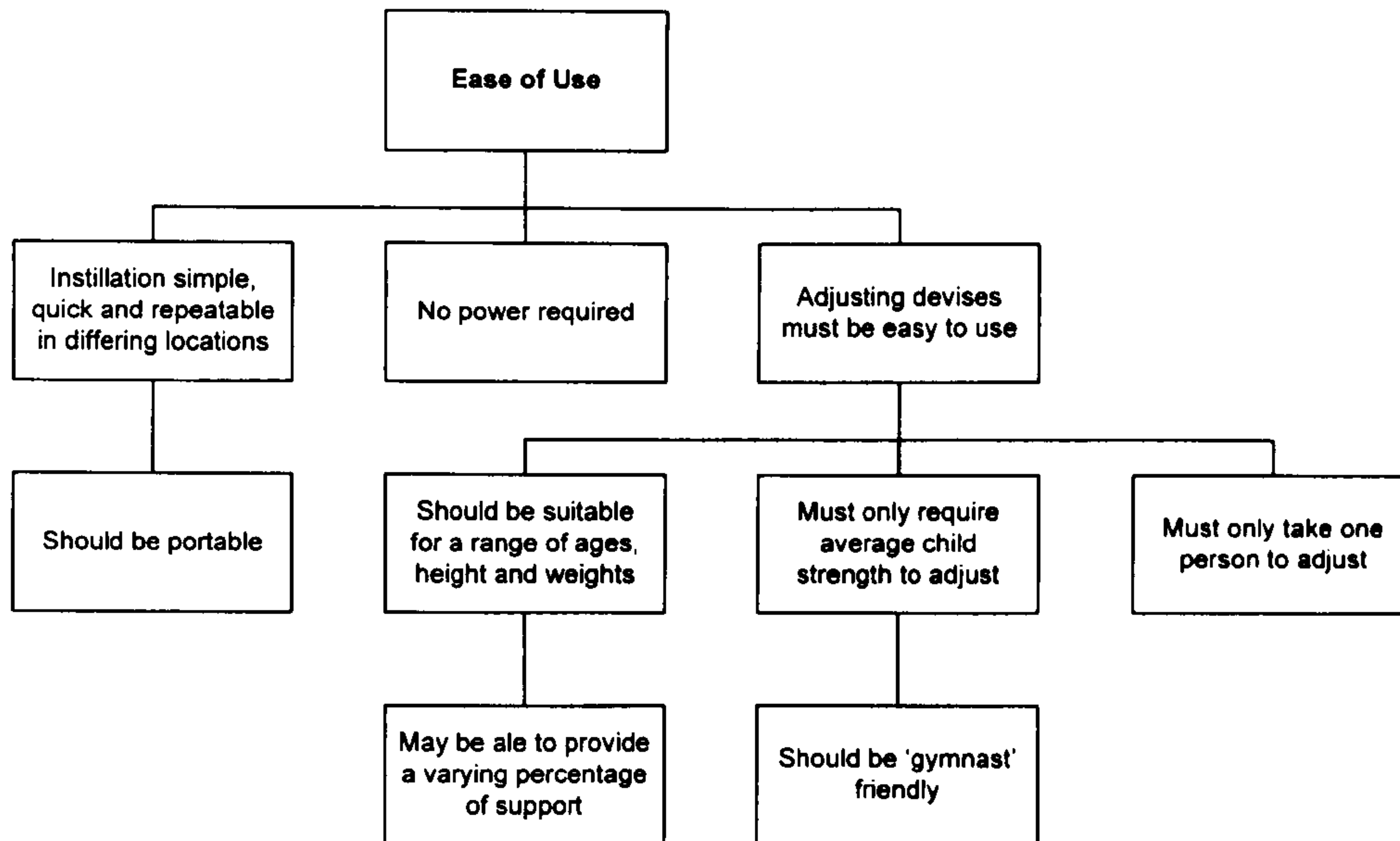


Figure B-3: Sub level 1.2 of requirement tree.

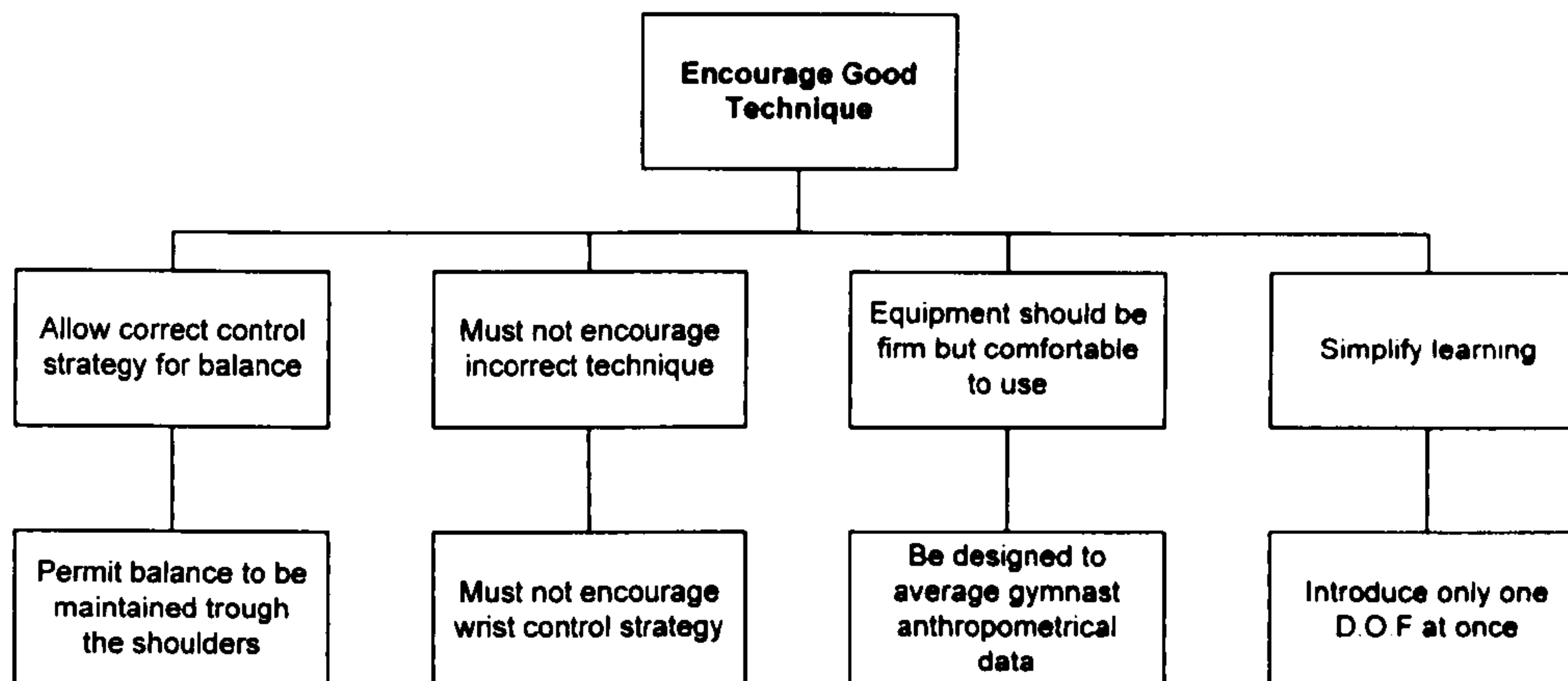


Figure B-4: Sub level 1.3 of requirement tree for handstand on the rings.

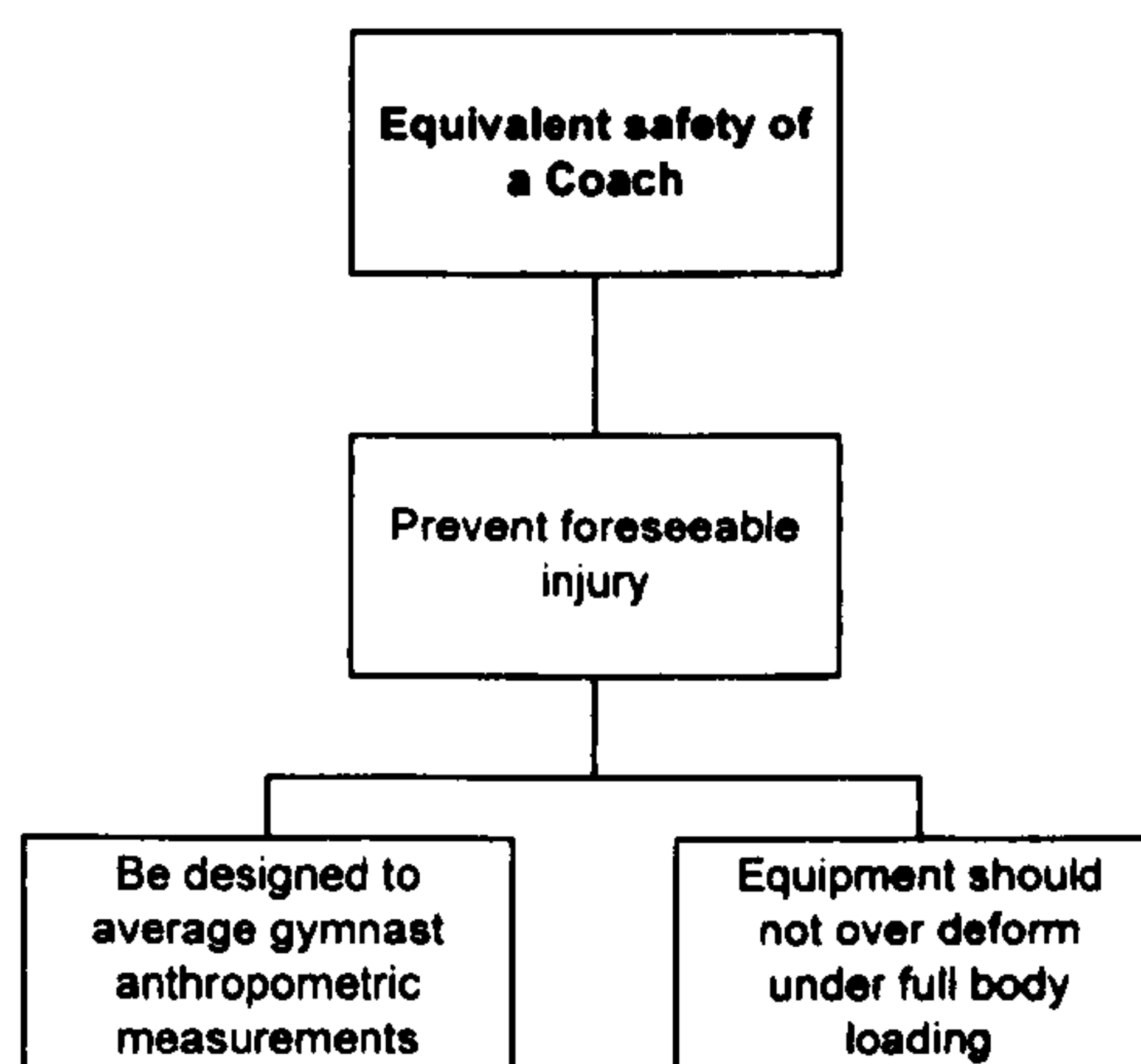


Figure B-5: Sub level 1.4 of requirement tree.

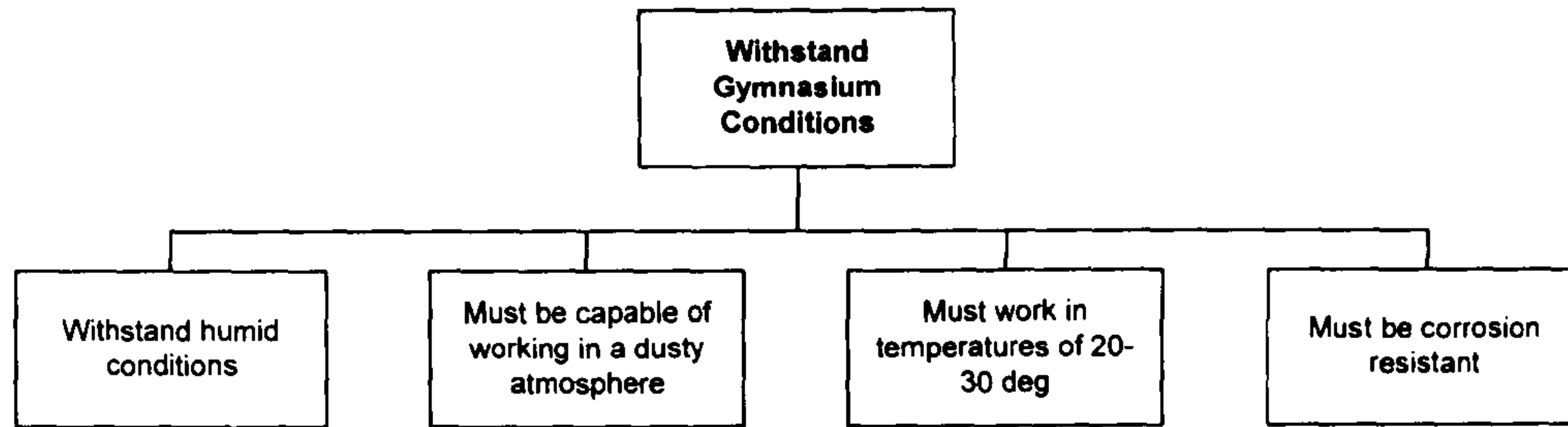


Figure B-6: Sub level 1.5 of requirement tree.

Appendix B2 – Backward handspring

All of the paths are the same for this training aid, except for 'Encouraging good technique':

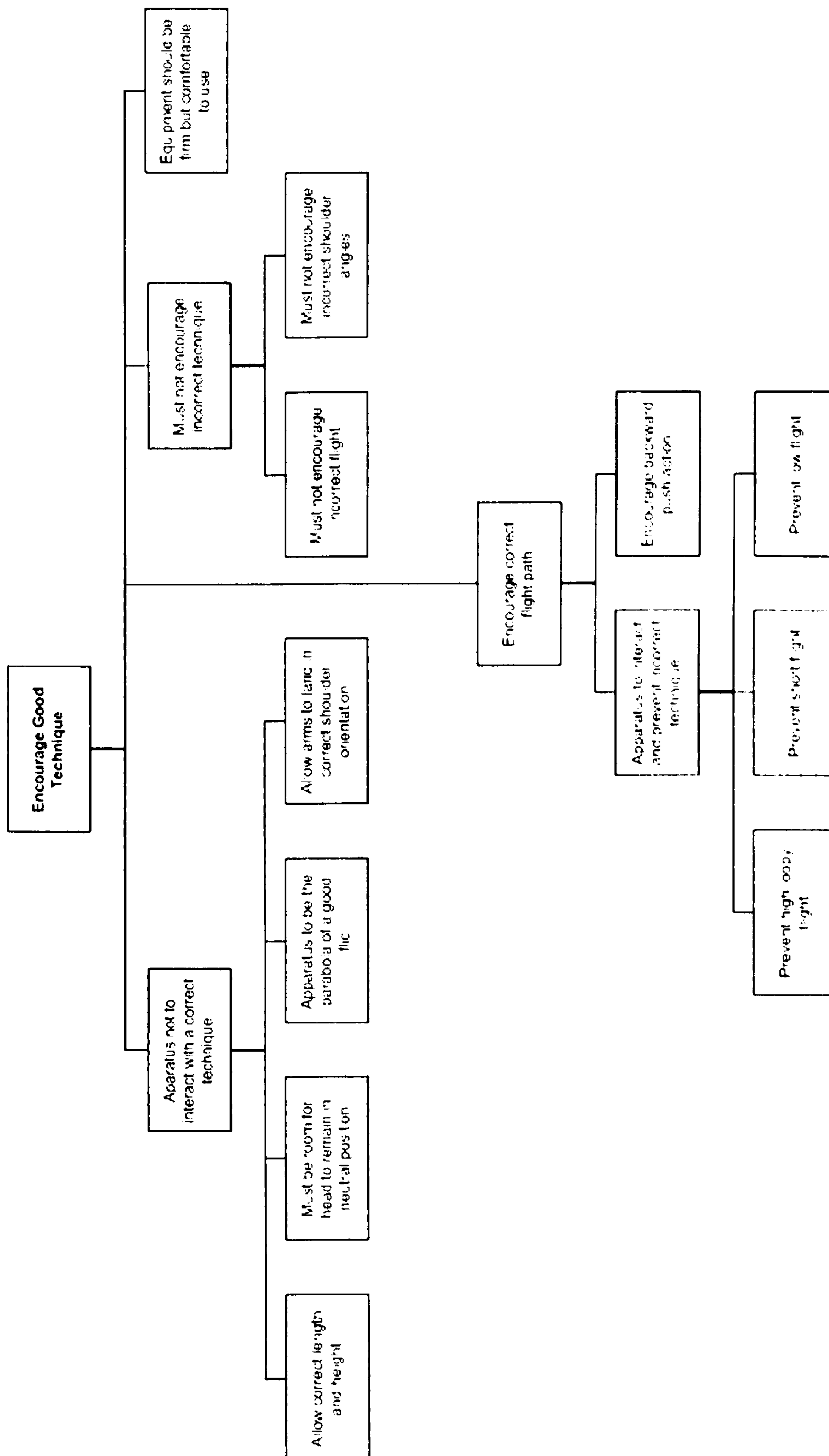


Figure B-7: Sub level 1.3 of requirement tree for backward handspring trainer.

Appendix C

Product Design Specifications

Appendix C1 – Rings handstand

Appendix C2 – Backward handspring

Appendix C1: Rings handstand training aid product design specification

1. Aesthetics

The equipment should:

- 1.1. Look of a suitable quality.
- 1.2. Be regarded as 'value for money'.
- 1.3. Look suitably rigid, strong and hard wearing.

2. Company constraints

- 2.1. Only one prototype will be produced to facilitate the required testing and assessments.
- 2.2. Limited manufacturing facilities and experience. Equipment will be designed within these constraints.

3. Customer requirements

The equipment must:

- 3.1. Correctly teach the correct control mechanism to hold a handstand balance on the rings.
- 3.2. Allow the natural mechanics of a correct technique to take place with out obstruction.
- 3.3. Simplify the learning phase of the balance.
- 3.4. Prevent any foreseeable serious injury from occurring.
- 3.5. Build confidence and understanding of move.
- 3.6. Lead on to unsupported performance.

4. Documentation

- 4.1. Documentation of any required testing will be obtained.

5. Environment

- 5.1. The equipment will be used inside under standard gymnasium conditions.
- 5.2. The product may experience a high dust content within the working atmosphere
- 5.3. The temperature will range between 20-30°C.
- 5.4. No power will be required.
- 5.5. The product may experience weather dependant humid conditions.
- 5.6. Corrosion resistance may be a consideration due to the presence of water and perspiration within the gymnasium

5.7. Any noise produced by the equipment should be within legal working limits for gymnastics equipment, of 80dB(A).

6. Ergonomics

6.1. Any adjusting devices must be located in suitable positions.

6.2. If applicable minimum strength should be required to alter equipment settings.

6.3. If applicable only one person should be required to alter equipment settings.

6.4. The equipment should be designed to general gymnastics anthropometrical data.

6.5. The equipment should not over deform during supporting full body weight (see *Safety*).

7. Installation

7.1. Installation should be simple, quick and easily repeatable in differing locations.

7.2. The installation should not require any specialise assistance.

7.3. No specialist testing must be required post equipment erection.

8. Legal

8.1. The design work will remain intellectual property of Emma Rosamond and Loughborough University.

8.2. The equipment will be designed within the legal standards for British gymnastics equipment, BS 1892-1, BS EN 913:1996, BS EN 957-1 : 1997, and BS 1892-3 : 2003

9. Life in service

9.1. The equipment should withstand average life expectations of gymnastics training equipment of one year with out maintenance.

9.2. The equipment should out live the standard product guarantee of one year.

10. Maintenance

10.1. After the first year, minimal maintenance should be required.

10.2. The equipment should remain safe to use, even if scheduled maintenance is forgotten.

10.3. If a single scheduled maintenance is not performed the equipment should remain in safe working order.

11. Manufacturing processes

11.1. Standard manufacturing processes available within Loughborough University must be utilised.

11.2. Minimal specialist manufacturing must be adopted.

11.3. Standard Gymnastics manufacturing processes must be conformed to.

11.4. Manufacturing must be simple and cost effective.

12. Performance

12.1. The equipment must be suitable for a range of ages, heights, weights and experience.

12.2. The equipment must be simple and easy to install and use.

12.3. The equipment should be 'gymnast friendly'.

12.4. The equipment may be able to provide varying percentages of support.

12.5. The equipment should be portable.

13. Processes

13.1. All components should comply with standard manufacturing requirements, or be a standard component of gymnastics equipment manufacture.

14. Product life span

14.1. The product may not reach commercial manufacture.

15. Quality and reliability

The equipment should:

15.1. Conform to BS and FIG quality standards.

15.2. Be capable of 1460 hours use with out evidence of wear, assuming 4hrs use per day.

15.3. Be capable of withstanding environmental conditions.

15.4. Must be capable of periods of continuous use.

16. Quantity

16.1. Only one prototype will be produced, unless significant alterations are required after preliminary testing.

17. Safety

The equipment must:

17.1. Withstand the specified loading range of a 70kg maximum load.

17.2. Withstand general 'ware and tear', with no detriment to gymnast safety.

17.3. British safety standards must be met (see *Standards and specifications*).

18. Size

18.1. The equipment will be modelled to occupy a specific area required to provide adequate space in which a novice gymnast will control a rings handstand.

18.2. The size of the equipment may possibly be altered for differing size of gymnast.

18.3. The size will be minimised to its precise requirements.

19. Standards and specifications

Standards to be adhered to:

- 19.1. Gymnasium equipment, Part 1: Specification for general requirements BS 1892-1, 1986.
- 19.2. Gymnastics equipment – General safety requirements and testing methods BS EN 913: 1996.
- 19.3. Stationary training equipment, Part 1: General safety requirements and test methods BS EN 957-1, 1997.
- 19.4. Sports mats – Part 3: Specification for fire safety requirements for mats, mattresses and landing areas BS 1892-3, 2003.
- 19.5. F.I.G. regulations for gymnastics equipment.

20. Target costs

- 20.1. All cost must be justifiable.
- 20.2. All cost must be kept to a minimum.

21. Testing

- 21.1. Safety testing must be within accordance of British Standard - Gymnastics equipment – General safety requirements and testing methods BS EN 913: 1996.
- 21.2. All required F.I.G. testing to be carried out.
- 21.3. Enforcement of the correct biomechanical path must be tested.
- 21.4. Continuity of muscle activity, body configuration, and joint path trajectories must be confirmed.
- 21.5. Gymnast 'comfort' must be assessed.
- 21.6. Reduction of gymnast anxiety must be assessed.

22. Weight

- 22.1. The weight of the equipment should be sufficient to aid in the dynamic stability of the product.
- 22.2. The product must be light enough for four gymnasts to move.

Appendix C2: Backward handspring training aid product design specification

1. Aesthetics

The equipment should:

- 1.1. Look of a suitable quality.
- 1.2. Be regarded as 'value for money'.
- 1.3. Be colourful and attractive to gymnasts of the required age ranges (5-7yrs elite, 12-16yrs general)

2. Company constraints

- 2.1. Only one prototype will be produced to facilitate the required testing and assessments.
- 2.2. Limited manufacturing facilities and experience. Equipment will be designed within these constraints.

3. Customer requirements

The equipment must:

- 3.1. Support the gymnast throughout first phase of backward handspring if the move is performed incorrectly.
- 3.2. Allow the natural mechanics of a correct technique to take place without obstruction.
- 3.3. Enforce the correct biomechanical path.
- 3.4. Prevent any foreseeable serious injury from occurring.
- 3.5. Alleviate anxiety of move.
- 3.6. Build confidence and understanding of move.
- 3.7. Lead on to unsupported performance.
- 3.8. Alleviate requirement for support from coach.
- 3.9. Be able to be used un supervised.

4. Documentation

- 4.1. Documentation of any required testing will be obtained.

5. Environment

- 5.1. The equipment will be used indoors under standard gymnasium conditions.
- 5.2. The equipment may experience a high dust content within the working atmosphere
- 5.3. The temperature will range between 20-30°C.
- 5.4. No power will be required.
- 5.5. The product may experience weather dependant humid conditions.

5.6. Corrosion resistance may be a consideration due to the presence of water and perspiration within the gymnasium.

5.7. Any noise produced by the equipment should be within legal working limits for gymnastics equipment, of 80dB(A).

6. Ergonomics

6.1. Any adjusting devices must be located in suitable positions.

6.2. If applicable minimum strength should be required to alter equipment settings.

6.3. If applicable only one person should be required to alter equipment settings.

6.4. The equipment should be designed to general gymnastics anthropometrical data.

6.5. The equipment should not permanently or excessively deform during supporting full body weight (see *Safety*).

7. Installation

7.1. Installation should be simple, quick and easily repeatable in differing locations.

7.2. The installation should not require any specialist assistance.

7.3. No specialist testing must be required, post equipment erection.

8. Legal

8.1. The design work will remain intellectual property of Emma Rosamond and Loughborough University.

8.2. The equipment will be designed within the legal standards for British gymnastics equipment, BS 1892-1, BS EN 913:1996, BS EN 957-1 : 1997, and BS 1892-3 : 2003

9. Life in service

9.1. The equipment should withstand average life expectations of gymnastics training equipment of one year without maintenance.

9.2. The equipment should out live the standard product guarantee of one year.

10. Maintenance

10.1. After the first year, minimal maintenance should be required.

10.2. The equipment should remain safe to use, even if scheduled maintenance is forgotten.

10.3. If a single scheduled maintenance is not performed the equipment should remain in safe working order.

11. Manufacturing processes

11.1. Standard manufacturing processes available within Loughborough University must be utilised.

11.2. Minimal specialist manufacturing must be adopted.

11.3. Standard Gymnastics manufacturing processes must be conformed to.

11.4. Manufacturing must be simple and cost effective.

12. Performance

12.1. The equipment must be suitable for a range of ages, heights, weights and experience.

12.2. The equipment must be simple and easy to install and use.

12.3. The equipment should be 'gymnast friendly'.

12.4. May be able to provide varying percentages of support.

12.5. The equipment should be portable.

13. Processes

13.1. All components should comply with standard manufacturing requirements, or be a standard component of gymnastics equipment manufacture.

14. Product life span

14.1. The product may not reach commercial manufacture.

15. Quality and reliability

The equipment should:

15.1. Conform to BS and FIG relevant quality standards.

15.2. Be capable of 1460 hours use without evidence of wear, assuming 4hrs use per day.

15.3. Be capable of withstanding environmental conditions.

15.4. Must be capable of periods of continuous use.

16. Quantity

16.1. Only one prototype will be produced, unless significant alterations are required after preliminary testing.

17. Safety

The equipment must:

17.1. Withstand the specified loading range for which 70kg is a maximum.

17.2. Withstand general 'wear and tear', with no detriment to gymnast safety.

17.3. British safety standards must be met (see *Standards and specifications*).

18. Size

18.1. The equipment will be modelled to occupy a specific area required to support a typical back backward handspring.

18.2. The size of the equipment may possibly be altered for differing size of gymnast.

18.3. The size shall be of the minimum required to meet the design specifications.

19. Standards and specifications

Standards to be adhered to:

- 19.1. Gymnasium equipment, Part 1: Specification for general requirements BS 1892-1, 1986.
- 19.2. Gymnastics equipment – General safety requirements and testing methods BS EN 913: 1996.
- 19.3. Stationary training equipment, Part 1: General safety requirements and test methods BS EN 957-1, 1997.
- 19.4. Sports mats – Part 3: Specification for fire safety requirements for mats, mattresses and landing areas BS 1892-3, 2003.
- 19.5. F.I.G. regulations for gymnastics equipment.

20. Target costs

- 20.1. All cost must be justifiable.
- 20.2. All cost must be kept to a minimum, and not exceed priced which gymnasiums will accept.

21. Testing

- 21.1. Safety testing must be within accordance of British Standard - Gymnastics equipment – General safety requirements and testing methods BS EN 913: 1996.
- 21.2. All required F.I.G. testing to be carried out.
- 21.3. Enforcement of the correct biomechanical path must be tested.
- 21.4. Continuity of limb speeds, body angles, and path trajectories must be confirmed.
- 21.5. Gymnast 'comfort' must be assessed.
- 21.6. Reduction of gymnast anxiety must be assessed.

22. Weight

- 22.1. The weight of the equipment should be sufficient to aid in the dynamic stability of the product.
- 22.2. The product must be light enough for four gymnasts to move.

Appendix D

Model of a Handstand on a Frictionless Surface Chapter 4

Appendix D1 – Full maths description from Chapter 4

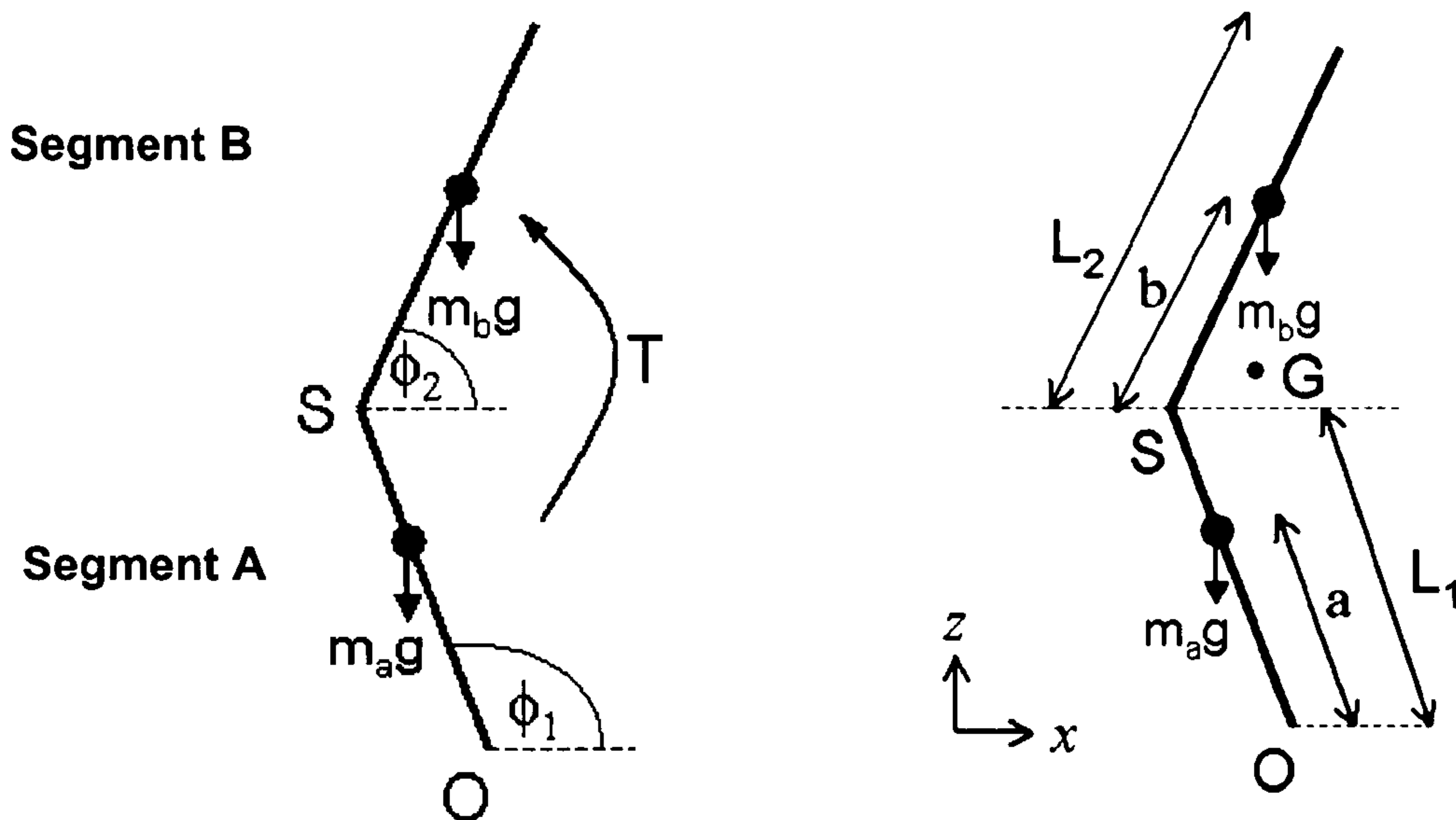


Figure D-1: Model of the handstand on a surface free to move horizontally.

Shoulder Strategy

A torque T is applied at the shoulder joint S , in order to control the balance by ensuring that the whole body mass centre G is in close vertical alignment with the hands O . The method used to obtain the equations of motion for this system are similar to that of Yeadon and Trewartha (2003) which resulted in an equation of motion of the form $\ddot{X} = k^2x - eT$ where T was the joint torque, X was the mass centre displacement and k and e were constants. For this system it was shown that stable control could be effected using control in the form $T = px + d\dot{x}$ providing the time delay was not too great. It is anticipated that a similar equation of motion will be obtained for the rings handstand using a shoulder torque to control the system.

During a handstand on the rings as the mass centre does not move horizontally, $\dot{x}_G = \ddot{x}_G = 0$, and all measurements are made from a fixed location, so without loss of generality $x_G = 0$.

Taking moments about S for segment B gives:

Torque = rate of change of angular momentum

$$T - m_b g(x_b - x_s) = I_b \ddot{\phi}_2 - m_b \ddot{x}_b(z_b - z_s) + m_b \ddot{z}_b(x_b - x_s) \quad (1)$$

Taking moments about O for the whole system gives:

Torque = rate of change of angular momentum

$$\begin{aligned}
 -m_a g(x_a - x_o) - m_b g(x_b - x_o) = I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - m_a \ddot{x}_a(z_a - z_o) + m_a \ddot{z}_a(x_a - x_o) \\
 - m_b \ddot{x}_b(z_b - z_o) + m_b \ddot{z}_b(x_b - x_o) \quad (2)
 \end{aligned}$$

where segments A and B have mass centres (x_a, z_a) and (x_b, z_b) , masses m_a , and m_b , and moments of inertia I_a and I_b about their respective mass centres.

Assuming that ϕ_1 and ϕ_2 remain close to $\pi/2$, throughout the balance, the motion of the mass centres a and b will be primarily horizontal so that \ddot{z}_a and \ddot{z}_b may be neglected and $\sin\phi_1$ and $\sin\phi_2$ may be approximated as 1.

From the model:

$$\begin{aligned}
 x_a - x_o &= a \cos \phi_1 \\
 x_s - x_o &= L_1 \cos \phi_1 \\
 x_b - x_s &= b \cos \phi_2
 \end{aligned}$$

Summing these last two equations:

$$x_b - x_o = L_1 \cos \phi_1 + b \cos \phi_2$$

Rearranging and differentiating:

$$\begin{aligned}
 x_a &= x_o + a \cos \phi_1 \\
 \dot{x}_a &= \dot{x}_o - a \sin \phi_1 \dot{\phi}_1 \\
 \ddot{x}_a &= \ddot{x}_o - a \sin \phi_1 \ddot{\phi}_1 - a \cos \phi_1 \dot{\phi}_1^2 \quad (3)
 \end{aligned}$$

$$\begin{aligned}
 x_b &= x_o + L_1 \cos \phi_1 + b \cos \phi_2 \\
 \dot{x}_b &= \dot{x}_o - L_1 \sin \phi_1 \dot{\phi}_1 - b \sin \phi_2 \dot{\phi}_2 \\
 \ddot{x}_b &= \ddot{x}_o - L_1 \sin \phi_1 \ddot{\phi}_1 - L_1 \cos \phi_1 \dot{\phi}_1^2 - b \sin \phi_2 \ddot{\phi}_2 - b \cos \phi_2 \dot{\phi}_2^2 \quad (4)
 \end{aligned}$$

$$\begin{aligned}
 x_s &= x_o + L_1 \cos \phi_1 \\
 \dot{x}_s &= \dot{x}_o - L_1 \sin \phi_1 \dot{\phi}_1 \\
 \ddot{x}_s &= \ddot{x}_o - L_1 \sin \phi_1 \ddot{\phi}_1 - L_1 \cos \phi_1 \dot{\phi}_1^2 \quad (5)
 \end{aligned}$$

Similarly:

$$\begin{aligned}
 z_a - z_o &= a \sin \phi_1 \\
 z_s - z_o &= L_1 \sin \phi_1 \\
 z_b - z_s &= b \sin \phi_2 \quad , \text{ where } z_o = 0.
 \end{aligned}$$

Summing these last two equations:

$$z_b - z_o = L_1 \sin \phi_1 + b \sin \phi_2$$

Rearranging and differentiating

$$\begin{aligned} z_a &= z_o + a \sin \phi_1 \\ \dot{z}_a &= \dot{z}_o + a \cos \phi_1 \dot{\phi}_1 \\ \ddot{z}_a &= \ddot{z}_o + a \cos \phi_1 \ddot{\phi}_1 - a \sin \phi_1 \dot{\phi}_1^2 \end{aligned} \quad (6)$$

$$\begin{aligned} z_b &= z_o + L_1 \sin \phi_1 + b \sin \phi_2 \\ \dot{z}_b &= \dot{z}_o + L_1 \cos \phi_1 \dot{\phi}_1 + b \cos \phi_2 \dot{\phi}_2 \\ \ddot{z}_b &= \ddot{z}_o + L_1 \cos \phi_1 \ddot{\phi}_1 - L_1 \sin \phi_1 \dot{\phi}_1^2 + b \cos \phi_2 \ddot{\phi}_2 - b \sin \phi_2 \dot{\phi}_2^2 \end{aligned} \quad (7)$$

$$\begin{aligned} z_s &= z_o + L_1 \sin \phi_1 \\ \dot{z}_s &= \dot{z}_o + L_1 \cos \phi_1 \dot{\phi}_1 \\ \ddot{z}_s &= \ddot{z}_o + L_1 \cos \phi_1 \ddot{\phi}_1 - L_1 \sin \phi_1 \dot{\phi}_1^2 \end{aligned} \quad (8)$$

From the definition of the whole body mass centre G:

$$(m_a + m_b)x_g = m_a x_a + m_b x_b = 0, \text{ since } x_g = 0 \text{ as there are no external horizontal forces.}$$

Therefore:

$$m_a x_a = -m_b x_b \quad (9)$$

Substituting the expressions for x_a and x_b in equation (9) to find x_o :

$$\begin{aligned} m_a (x_o + a \cos \phi_1) &= -m_b (x_o + L_1 \cos \phi_1 + b \cos \phi_2) \\ x_o + a \cos \phi_1 &= -\frac{m_b}{m_a} (x_o + L_1 \cos \phi_1 + b \cos \phi_2) \\ x_o + a \cos \phi_1 &= -\frac{m_b}{m_a} x_o - \frac{m_b}{m_a} (L_1 \cos \phi_1 + b \cos \phi_2) \\ x_o + \frac{m_b}{m_a} x_o &= -\frac{m_b}{m_a} (L_1 \cos \phi_1 + b \cos \phi_2) - a \cos \phi_1 \\ x_o \left(1 + \frac{m_b}{m_a} \right) &= -\frac{m_b}{m_a} (L_1 \cos \phi_1 + b \cos \phi_2) - a \cos \phi_1 \end{aligned}$$

Let $\frac{m_b}{m_a} = \mu$ so that:

$$x_o = \frac{-\mu}{(\mu+1)}(L_1 \cos \phi_1 + b \cos \phi_2) - \frac{a \cos \phi_1}{(\mu+1)} \quad (10)$$

Through the conservation of linear momentum:

$$m_1 v_1 = m_2 v_2$$

$$(m_a + m_b) \dot{x}_g = m_a \dot{x}_a + m_b \dot{x}_b = 0$$

Therefore:

$$m_a \dot{x}_a = -m_b \dot{x}_b \quad (11)$$

Substituting expressions for \dot{x}_a and \dot{x}_b in equation (11) with $\frac{m_b}{m_a} = \mu$ to find \dot{x}_o

$$\dot{x}_a = -\mu \dot{x}_b$$

$$\dot{x}_o - a \sin \phi_1 \dot{\phi}_1 = -\mu(\dot{x}_o - L_1 \sin \phi_1 \dot{\phi}_1 - b \sin \phi_2 \ddot{\phi}_2)$$

$$\dot{x}_o + \mu \dot{x}_o = \mu(L_1 \sin \phi_1 \dot{\phi}_1 + b \sin \phi_2 \ddot{\phi}_2) + a \sin \phi_1 \dot{\phi}_1$$

$$\dot{x}_o(1 + \mu) = \mu(L_1 \sin \phi_1 \dot{\phi}_1 + b \sin \phi_2 \ddot{\phi}_2) + a \sin \phi_1 \dot{\phi}_1$$

$$\dot{x}_o = \frac{\mu}{(1 + \mu)}(L_1 \sin \phi_1 \dot{\phi}_1 + b \sin \phi_2 \ddot{\phi}_2) + \frac{1}{(1 + \mu)}(a \sin \phi_1 \dot{\phi}_1) \quad (12)$$

which agrees with the derivative of equation (10).

Using Newton's Second Law horizontally:

$$F = ma$$

$$0 = (m_a + m_b) \ddot{x}_g = m_a \ddot{x}_a + m_b \ddot{x}_b, \text{ as there are no horizontal frictional forces.}$$

Therefore:

$$m_a \ddot{x}_a = -m_b \ddot{x}_b \quad (13)$$

Substituting expressions for \ddot{x}_a and \ddot{x}_b in equation (13) to find \ddot{x}_o :

$$\text{Using } \frac{m_b}{m_a} = \mu$$

$$\ddot{x}_o = -\mu \ddot{x}_b$$

$$\ddot{x}_o - a \cos \phi_1 \dot{\phi}_1^2 - a \sin \phi_1 \ddot{\phi}_1 = -\mu(\ddot{x}_o - L_1 \cos \phi_1 \dot{\phi}_1^2 - L_1 \sin \phi_1 \ddot{\phi}_1 - b \cos \phi_2 \dot{\phi}_2^2 - \sin \phi_2 \ddot{\phi}_2)$$

$$\ddot{x}_o - \mu \ddot{x}_o = -\mu(L_1 \cos \phi_1 \dot{\phi}_1^2 + L_1 \sin \phi_1 \ddot{\phi}_1 + b \cos \phi_2 \dot{\phi}_2^2 + \sin \phi_2 \ddot{\phi}_2) + a \cos \phi_1 \dot{\phi}_1^2 + a \sin \phi_1 \ddot{\phi}_1$$

$$\ddot{x}_o = \frac{\mu}{(\mu+1)} (L_1 \cos \phi_1 \dot{\phi}_1^2 + L_1 \sin \phi_1 \ddot{\phi}_1 + b \cos \phi_2 \dot{\phi}_2^2 + b \sin \phi_2 \ddot{\phi}_2) + \frac{1}{(\mu+1)} (a \cos \phi_1 \dot{\phi}_1^2 + a \sin \phi_1 \ddot{\phi}_1) \quad (14)$$

which agrees with the derivative of equation (12).

From equation (1):

$$T - m_b g(x_b - x_s) = I_b \ddot{\phi}_2 - m_b \ddot{x}_b (z_b - z_s) + m_b \ddot{z}_b (x_b - x_s)$$

Substituting for $(x_b - x_s)$ and $(z_b - z_s)$:

$$T - m_b g(b \cos \phi_2) = I_b \ddot{\phi}_2 - m_b \ddot{x}_b (b \sin \phi_2) + m_b \ddot{z}_b (b \cos \phi_2) \quad (15)$$

From (14) equation (4) becomes:

$$\ddot{x}_b = \frac{-1}{(\mu+1)} (L_1 \cos \phi_1 \dot{\phi}_1^2 + L_1 \sin \phi_1 \ddot{\phi}_1 + b \cos \phi_2 \dot{\phi}_2^2 + b \sin \phi_2 \ddot{\phi}_2) + \frac{1}{(\mu+1)} (a \cos \phi_1 \dot{\phi}_1^2 + a \sin \phi_1 \ddot{\phi}_1) \quad (16)$$

and equation (7) become:

$$\ddot{z}_b = L_1 \cos \phi_1 \ddot{\phi}_1 - L_1 \sin \phi_1 \dot{\phi}_1^2 + b \cos \phi_2 \ddot{\phi}_2 - b \sin \phi_2 \dot{\phi}_2^2, \text{ since } \ddot{z}_0 = 0 \quad (17)$$

From equation (2):

$$\begin{aligned} -m_a g(x_a - x_o) - m_b g(x_b - x_o) &= I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - m_a \ddot{x}_a (z_a - z_o) - m_b \ddot{x}_b (z_b - z_o) \\ &\quad + m_b \ddot{z}_b (x_b - x_o) + m_a \ddot{z}_a (x_a - x_o) \end{aligned}$$

Substituting for $(x_a - x_o)$, $(x_b - x_o)$, $(z_a - z_o)$ and $(z_b - z_o)$ and using $m_a x_a + m_b x_b = m x_g$:

$$\begin{aligned} -mg(x_g - x_o) &= I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - m_a \ddot{x}_a (a \sin \phi_1) - m_b \ddot{x}_b (L_1 \sin \phi_1 + b \sin \phi_2) \\ &\quad + m_b \ddot{z}_b (a \cos \phi_1) + m_a \ddot{z}_a (L_1 \sin \phi_1 + b \sin \phi_2) \end{aligned} \quad (18)$$

From (14) equation (3) becomes:

$$\ddot{x}_a = \frac{\mu}{(\mu+1)} (L_1 \cos \phi_1 \dot{\phi}_1^2 + L_1 \sin \phi_1 \ddot{\phi}_1 + b \cos \phi_2 \dot{\phi}_2^2 + b \sin \phi_2 \ddot{\phi}_2) - \frac{\mu}{(\mu+1)} (a \cos \phi_1 \dot{\phi}_1^2 + a \sin \phi_1 \ddot{\phi}_1) \quad (19)$$

and equation (6) becomes:

$$\ddot{z}_a = a \cos \phi_1 \ddot{\phi}_1 - a \sin \phi_1 \dot{\phi}_1^2, \text{ since } \ddot{z}_0 = 0 \quad (20)$$

Now it can be seen that $\ddot{x}_a = -\mu \ddot{x}_b$ as a check.

Assuming that ϕ_1 and ϕ_2 remain close to $\pi/2$, so that $\cos\phi$ will be small and $\sin\phi$ will close to 1, using $\mu = \frac{m_b}{m_a}$ and equations (16) and (17), equation (15) becomes:

$$T - m_b g b \cos \phi_2 = I_b \ddot{\phi}_2 + \frac{m_a m_b}{m} b [L_1 \ddot{\phi}_1 + b \ddot{\phi}_2 + a \ddot{\phi}_1]$$

If T is then changed to $-T$ so that a positive torque corresponds to shoulder extension (closing the shoulder angle) the above equation becomes:

$$-T - m_b g b \cos \phi_2 = \frac{m_a m_b}{m} [bL_1 + ba] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} b^2 \right] \ddot{\phi}_2 \quad (21)$$

Using equations (16), (17), (19) and (20), equation (18) becomes:

$$\begin{aligned} -mg(x_g - x_o) &= I_a \ddot{\phi}_1 + I_b \ddot{\phi}_2 - \frac{m_a m_b}{m} a [L_1 \ddot{\phi}_1 + b \ddot{\phi}_2 - a \ddot{\phi}_1] + \frac{m_a m_b}{m} [L_1 + b] [L_1 \ddot{\phi}_1 + b \ddot{\phi}_2 + a \ddot{\phi}_1] \\ &= \left[I_a + \frac{m_a m_b}{m} [(L_1 + b)(L_1 + a) - aL_1 + a^2] \right] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} [(L_1 + b)b - ab] \right] \ddot{\phi}_2 \\ &= \left[I_a + \frac{m_a m_b}{m} [L_1^2 + bL_1 + ab + a^2] \right] \ddot{\phi}_1 + \left[I_b + \frac{m_a m_b}{m} [L_1 b + b^2 - ab] \right] \ddot{\phi}_2 \end{aligned} \quad (22)$$

Multiplying equation (22) by some constant $-\lambda$ to be determined, and then subtracting equation (21) gives:

$$\begin{aligned} \lambda mg(x_g - x_o) + m_b g b \cos \phi_2 + T &= - \left[\frac{m_a m_b}{m} [bL_1 + ba] \right] \ddot{\phi}_1 - \lambda \left[I_a + \frac{m_a m_b}{m} [L_1^2 + bL_1 + ab + a^2] \right] \ddot{\phi}_1 \\ &\quad - \left[I_b + \frac{m_a m_b}{m} b^2 \right] \ddot{\phi}_2 - \lambda \left[I_b + \frac{m_a m_b}{m} [L_1 b + b^2 - ab] \right] \ddot{\phi}_2 \end{aligned} \quad (23)$$

Let $\frac{m_a m_b}{m} = \beta$, so that equation (23) becomes:

$$\begin{aligned} T + \lambda mg \left[(x_g - x_o) + \frac{m_b}{\lambda m} x_1 \right] &= -\ddot{\phi}_1 \left[\beta(bL_1 + ba) + \lambda \left(I_a + \beta(L_1^2 + bL_1 + ab + a^2) \right) \right] \\ &\quad - \ddot{\phi}_2 \left[(I_b + \beta b^2) + \lambda (I_b + \beta(L_1 b + b^2 - ab)) \right] \end{aligned} \quad (24)$$

$$\text{Where } x_1 = b \cos \phi_2 = x_b - x_s \quad (25)$$

$$\text{Let } X = (x_g - x_o) + \frac{m_b}{\lambda m} x_1 \quad (26)$$

Then double differentiating and multiplying by m :

$$m\ddot{X} = m(\ddot{x}_g - \ddot{x}_o) + \frac{m_b}{\lambda} \ddot{x}_1$$

$$m\ddot{X} = m_a(\ddot{x}_a - \ddot{x}_o) + m_b(\ddot{x}_b - \ddot{x}_o) + \frac{m_b}{\lambda} \ddot{x}_1 \quad (27)$$

Assuming that ϕ_1 and ϕ_2 remain close to $\pi/2$, throughout the balance $\sin\phi_1$ and $\sin\phi_2$ may be approximated as 1 and $\cos\phi_1$ and $\cos\phi_2$ may be approximated as 0. Therefore equations (3) (4) and (5) become:

$$\ddot{x}_a - \ddot{x}_o = -a\ddot{\phi}_1 \quad (28)$$

$$\ddot{x}_b - \ddot{x}_o = -L_1\ddot{\phi}_1 - b\ddot{\phi}_2 \quad (29)$$

$$\ddot{x}_s - \ddot{x}_o = -L_1\ddot{\phi}_1 \quad (30)$$

Double differentiating equation (25) gives $\ddot{x}_1 = \ddot{x}_b - \ddot{x}_s$ and subtracting equation (30) from equation (29) gives:

$$\ddot{x}_1 = -b\ddot{\phi}_2 \quad (31)$$

Therefore equation (27) becomes:

$$m\ddot{X} = -m_a a \ddot{\phi}_1 - m_b (L_1 \ddot{\phi}_1 + b \ddot{\phi}_2) - \frac{m_b}{\lambda} b \ddot{\phi}_2$$

$$m\ddot{X} = (-m_a a \ddot{\phi}_1 - m_b L_1 \ddot{\phi}_1) - m_b b \ddot{\phi}_2 - \frac{m_b}{\lambda} b \ddot{\phi}_2$$

$$m\ddot{X} = -(m_a a - m_b L_1) \ddot{\phi}_1 - m_b b \left[1 + \frac{1}{\lambda} \right] \ddot{\phi}_2 \quad (32)$$

Substituting equation (26) into equation (24) gives:

$$T + \lambda mgX = -\ddot{\phi}_1 \left[\beta(bL_1 + ba) + \lambda(I_a + \beta(L_1^2 + bL_1 + ab + a^2)) \right] \\ - \ddot{\phi}_2 \left[(I_b + \beta b^2) + \lambda(I_b + \beta(L_1 b + b^2 - ab)) \right] \quad (33)$$

To eliminate $\ddot{\phi}$ from the equation (33), if λ is chosen so that coefficients of $\ddot{\phi}_1$ and $\ddot{\phi}_2$ in equation (33) are each some constant ψ times the corresponding coefficient in equation (32), then equation (33) may be written as:

$$T + mg\lambda X = \psi m \ddot{X} \quad (34)$$

Or equivalently:

$$\ddot{X} = k^2 X - eT, \text{ where a suitable choice of } T \text{ should be given.} \quad (35)$$

$$\text{Where } k^2 = \frac{g\lambda}{\psi} \text{ and } e = \frac{1}{\psi m}$$

Therefore λ is given by the equation:

$$\frac{\lambda A + B}{\lambda C + D} = \frac{E}{\left(\frac{\lambda + 1}{\lambda}\right)F} \quad (36)$$

where:

$$A = I_a + \beta(L_1^2 + bL_1 + ab) + a^2$$

$$B = \beta(bL_1 + ba)$$

$$C = I_b + \beta(L_1 b + b^2 - ab)$$

$$D = I_b + \beta b^2$$

$$E = m_a a + m_b L_1$$

$$F = m_a b$$

Expanding and rearranging equation (36) gives the quadratic equation:

$$[AF - EC]\lambda^2 + [(A+B)F - DE]\lambda + BF = 0 \quad (37)$$

Control Strategy

The following the procedure of Yeadon and Trewartha (2003), from (35) the displacement X of the system is governed by the equation:

$$\ddot{X}_1(t) = k^2 X_1(t) - eT_1(t), \text{ where } t \text{ is the time.} \quad (38)$$

If T is based on the displacement X_1 and a velocity \dot{X}_1 at an earlier time, then the torques becomes:

$$T(t) = pX_1(t - t_0) + d\dot{X}_1(t - t_0) \quad (39)$$

which is an example of a closed loop PD control system.

Using the one-dimensional Taylor series, where by $X \equiv X_0 + \Delta X$, can be expanded to:

$$f(X_0 + \Delta X) = f(X_0) + \Delta X f'(X_0) + \frac{1}{2!}(\Delta X)^2 f''(X_0) + \dots$$

$X_1(t-t_0)$ and $\dot{X}_1(t-t_0)$ may be approximated as:

$$X_1(t-t_0) = X_1(t) - t_0\dot{X}_1(t) + \frac{1}{2}t_0^2\ddot{X}_1(t) \quad (40)$$

and

$$\dot{X}_1(t-t_0) = \dot{X}_1(t) - t_0\ddot{X}_1(t) \quad (41)$$

Substituting these expansions into equation (38) and rearranging gives:

$$\left[1 - \det_0 + \frac{1}{2}pet_0^2\right]\ddot{x}_1 + e[d - pt_0]\dot{x}_1 + [ep - k^2]x_1 = 0 \quad (42)$$

Which describes damped simple harmonic motion, $\alpha\ddot{x} + \beta\dot{x} + \omega_0^2x = 0$ (Kelly, 1993).

If each coefficient is positive in a damped simple harmonic motion equation, then stable control will have been achieved.

By analysing the coefficients, and rearranging them to produce limiting equations, the conditions for achieving positive coefficients leads to:

$$\frac{k^2}{e} < p < \frac{2}{et_0^2} \quad (43)$$

$$\frac{k^2t_0}{e} < d < \frac{2}{et_0} \quad (44)$$

and by combining the two equations above with the initial limiting equations:

$$\frac{1}{2kt_0} < \frac{p}{dk} < \frac{1}{kt_0} \quad (45)$$

Providing that the value of t_0 is not too large, there will a range of values for p and d which will satisfy the three limiting conditions described above in equations (43), (44), and (45).

If equation (45) is balanced to give a limiting value for p/d then:

$$\frac{1}{2}k^2t_0 = \frac{1}{t_0}, \text{ rearranging gives:}$$

$$t_0^2 = \frac{2}{k^2}, \text{ square rooting both sides of the equation gives the limiting value of } t_0:$$

$$t_0 = \frac{\sqrt{2}}{k} \quad (46)$$

Therefore inverting and substituting equation (46) back into equation (45) gives:

$$\frac{p}{d} = \frac{k}{\sqrt{2}} \quad (47)$$

Substituting into equation (44):

$$\frac{k^2 t_0}{e} = d \text{ then, } d = \frac{\sqrt{2}k}{e}$$

Summarising the work above:

The limiting value of t_0 is $\sqrt{2}/k$, with the corresponding values of $p = k^2/e$, and

$$d = \sqrt{2}k/e$$

Appendix E

Displacement Data from Chapter 6

Appendix E1 – Rings handstand comparisons

Appendix E1 – Rings handstand comparisons from Chapter 6

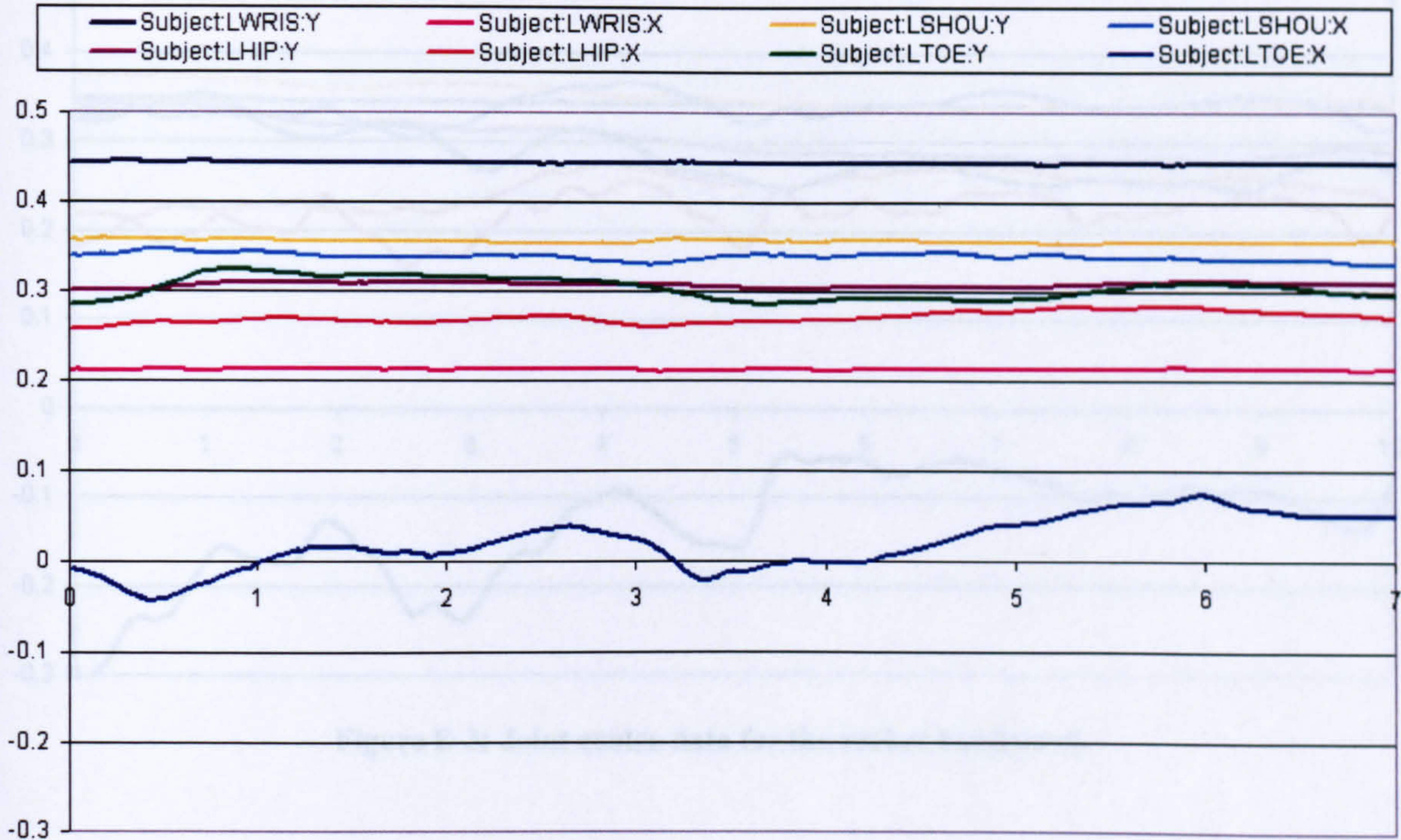


Figure E-1: Joint centre data for floor handstand.

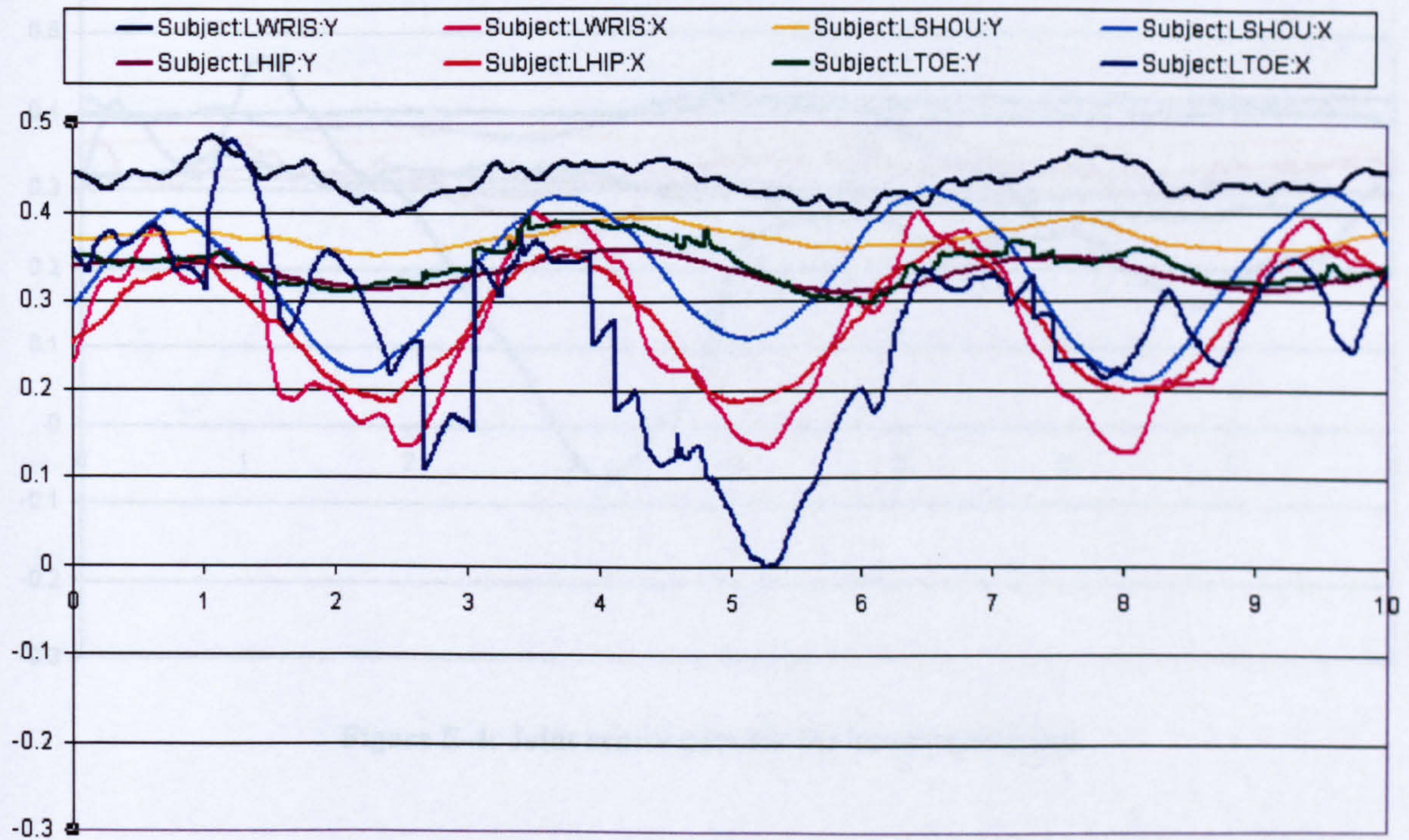


Figure E-2: Joint centre data for rings cable markers.

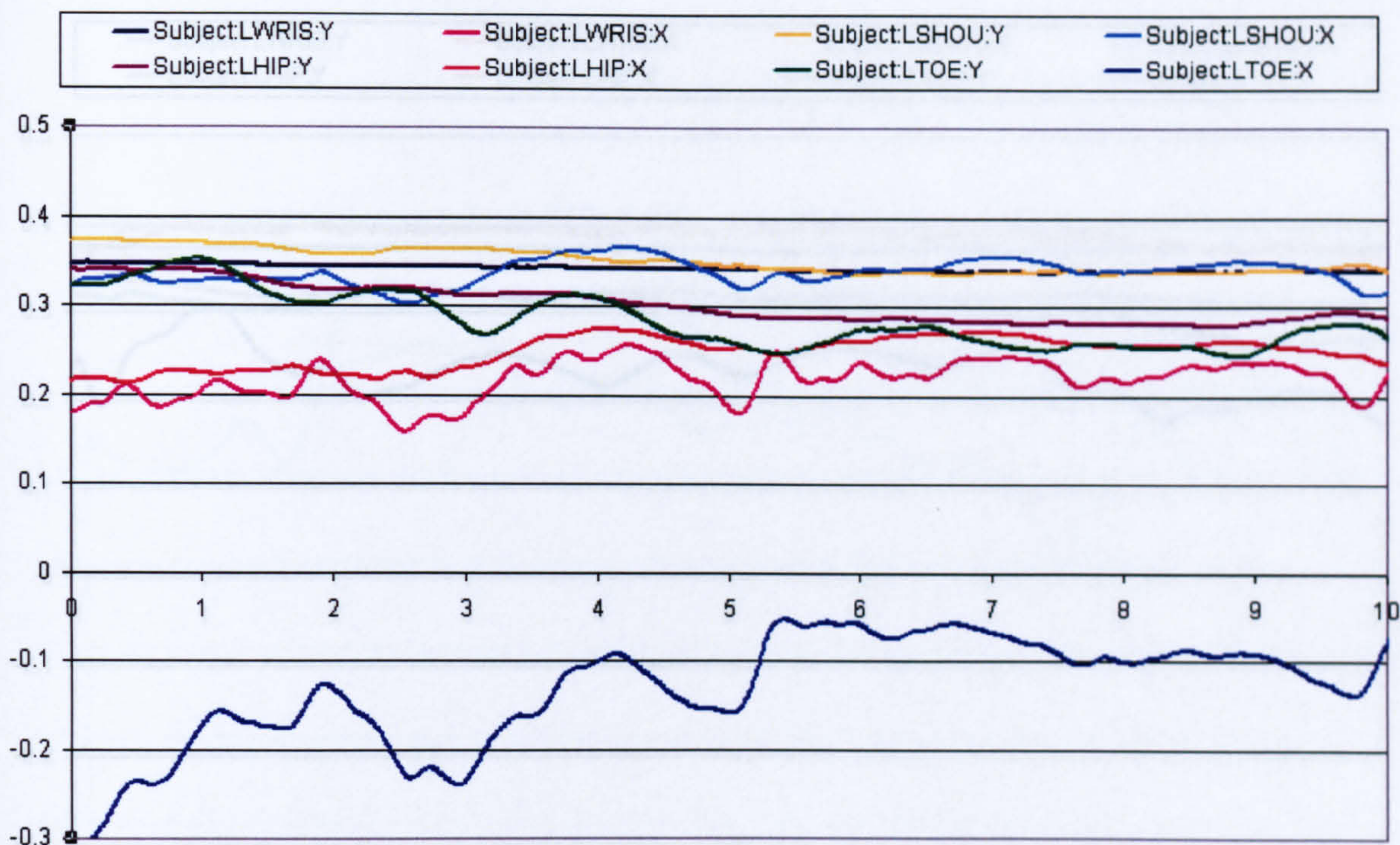


Figure E-3: Joint centre data for the rocker handstand.

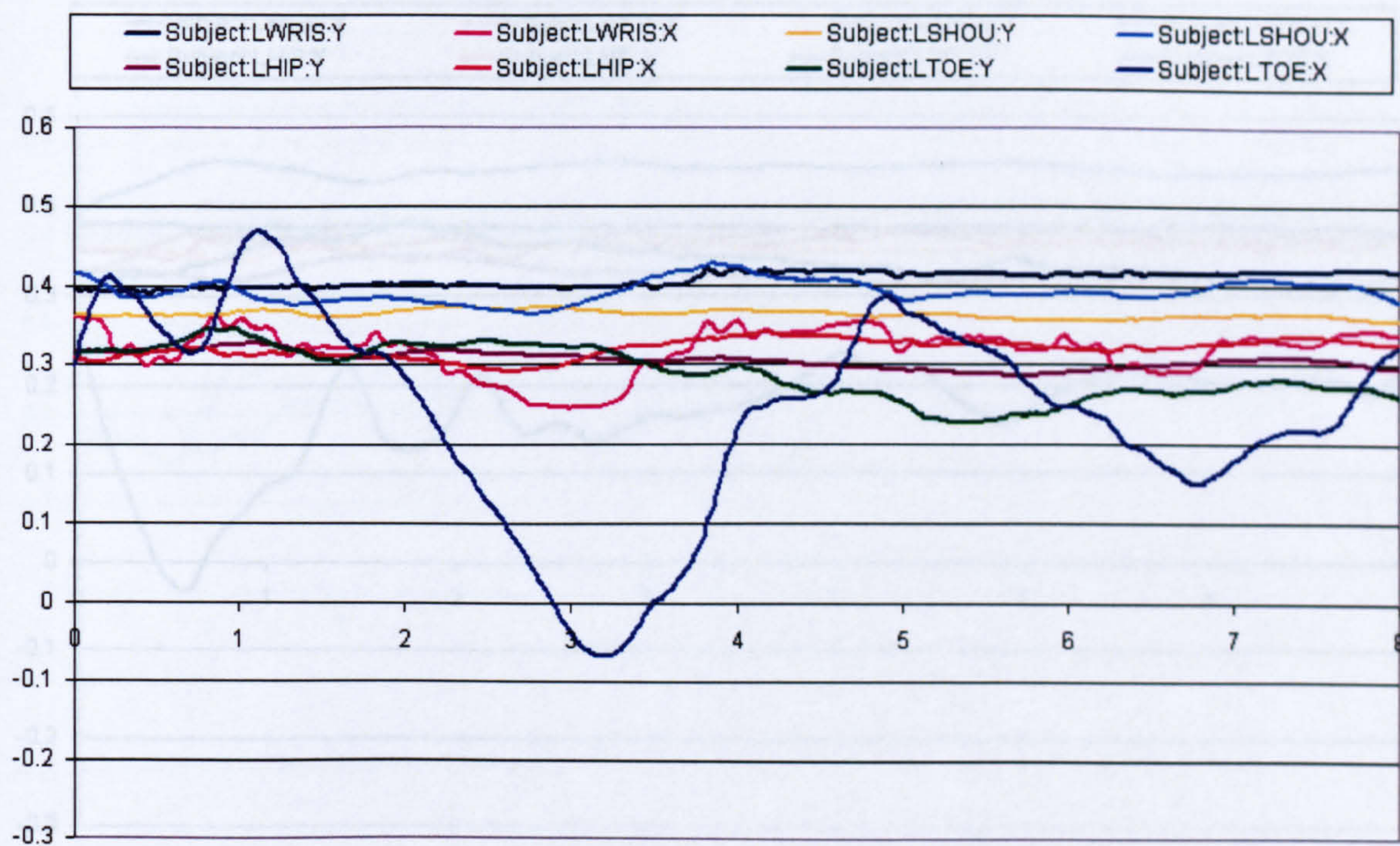


Figure E-4: Joint centre data for the bowls handstand.

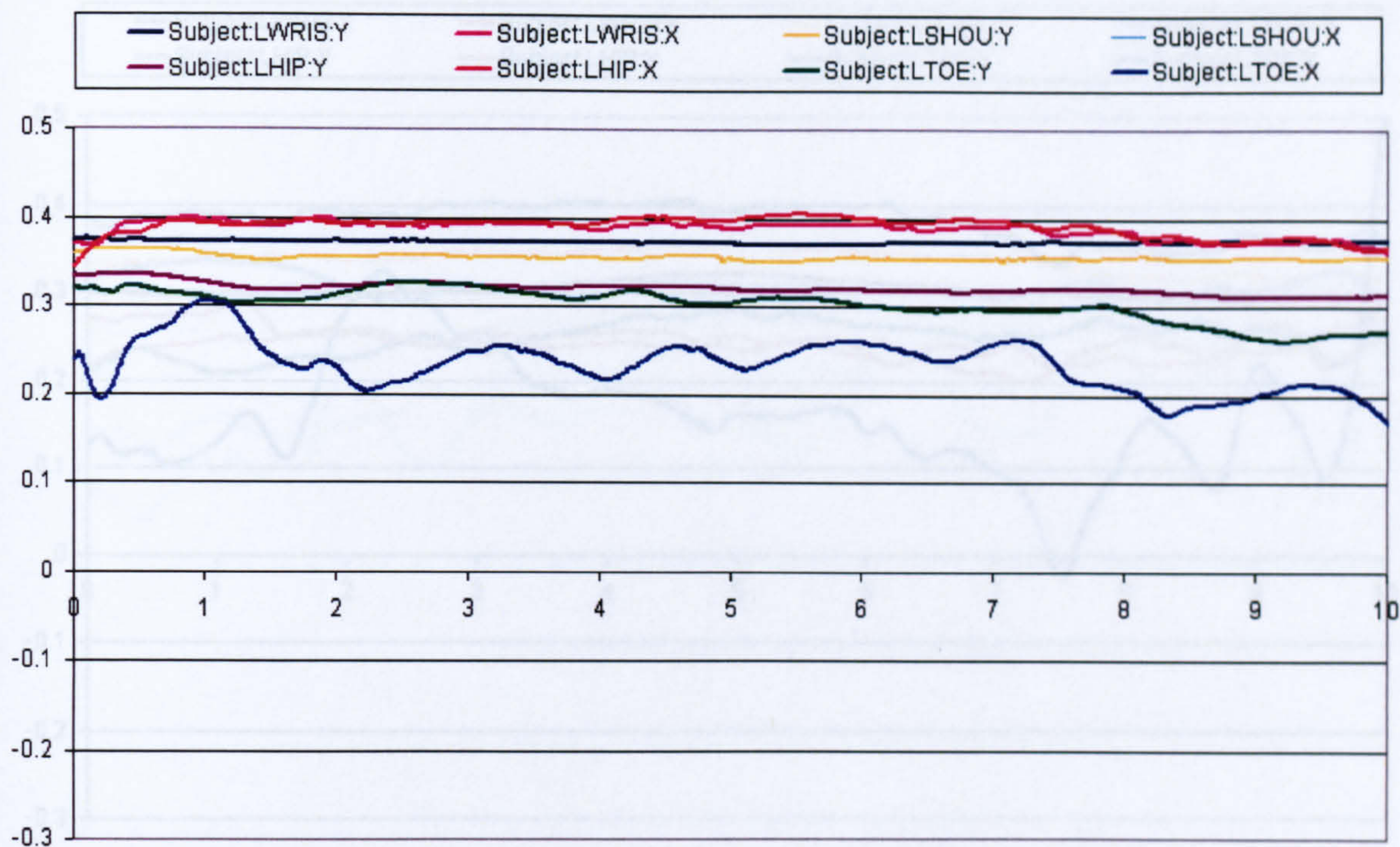


Figure E-5: Joint centre data for the rails 1 handstand.

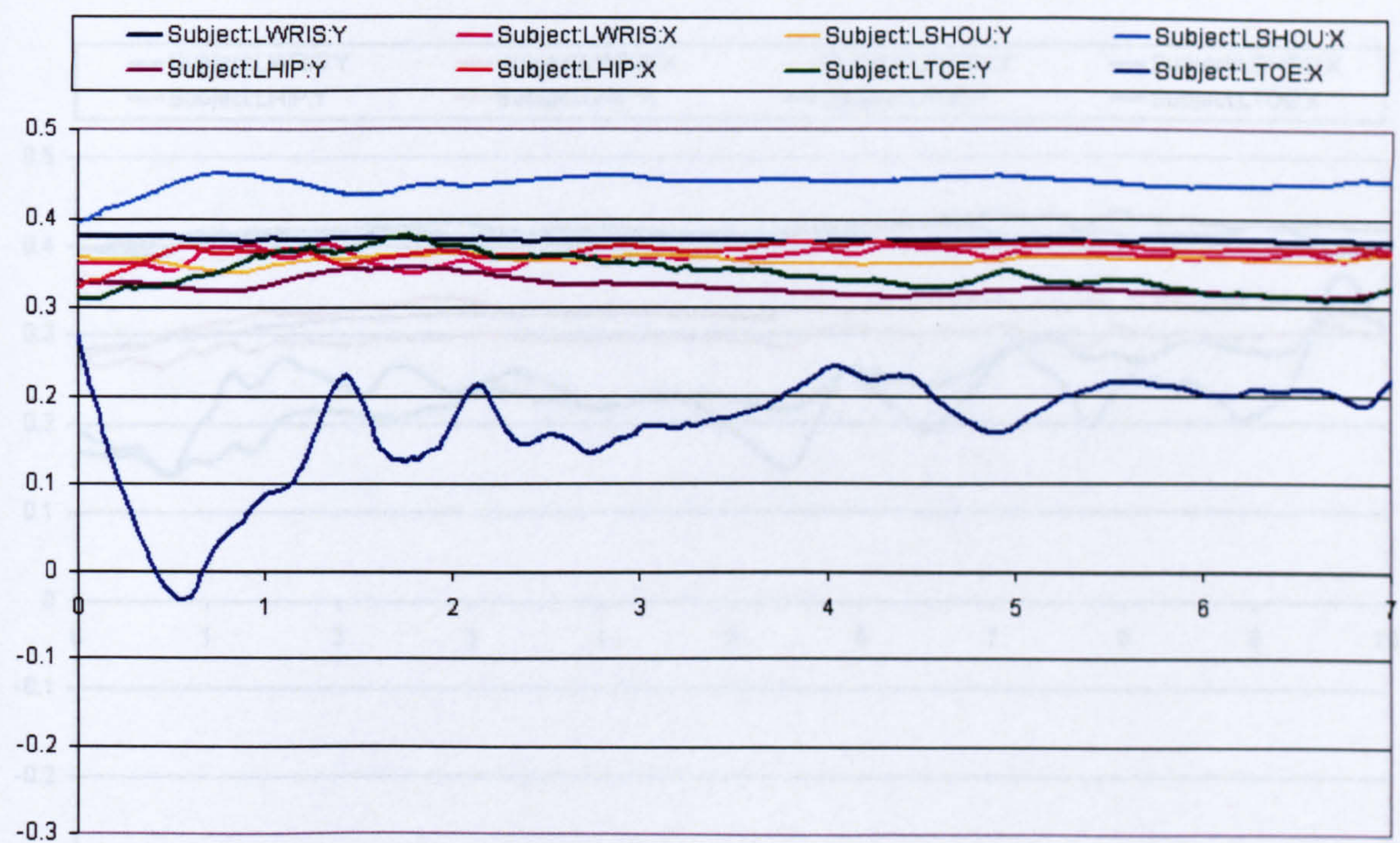


Figure E-6: Joint centre data for the rails 2 handstand.

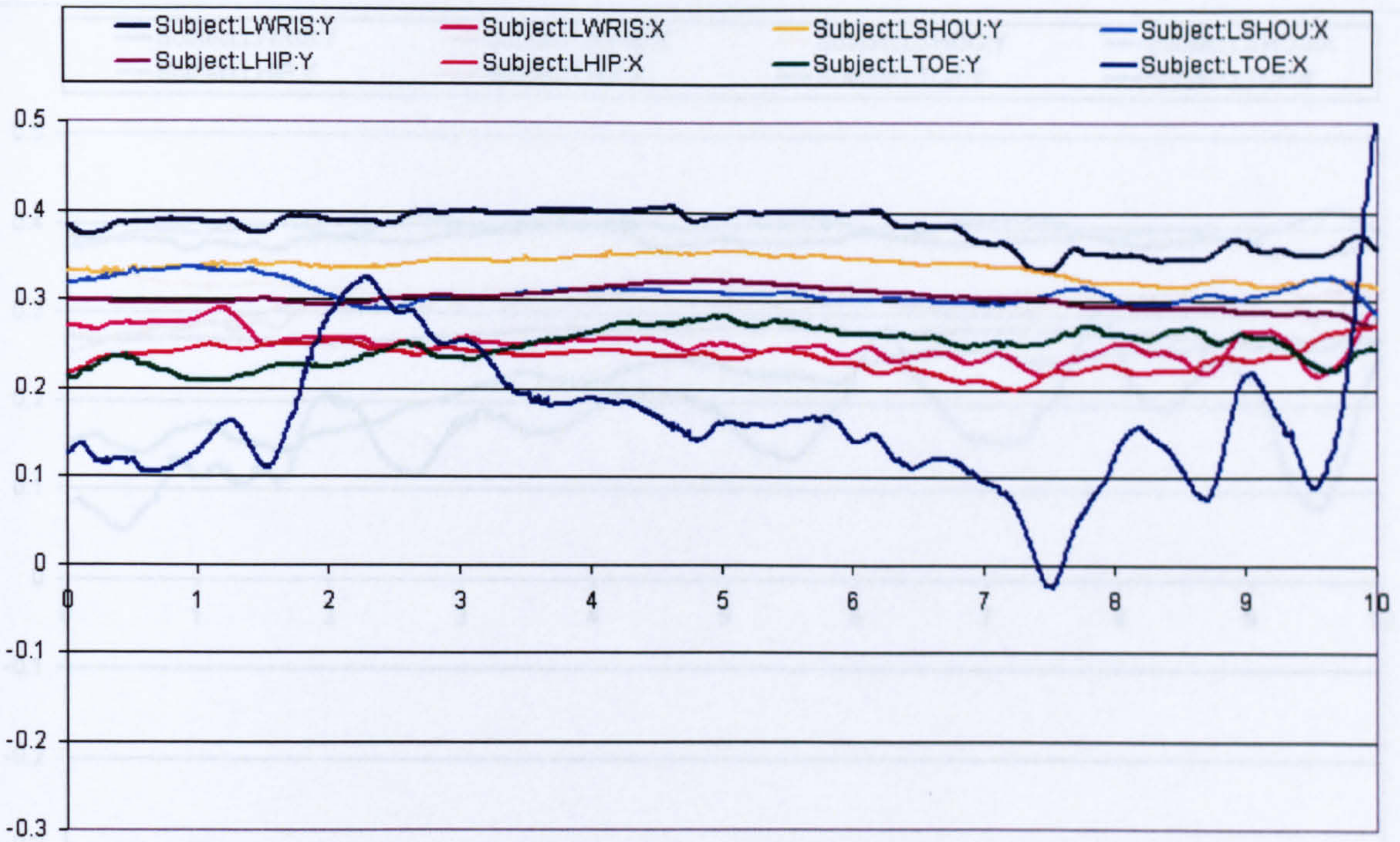


Figure E-7: Joint centre data for the rails 3 handstand.

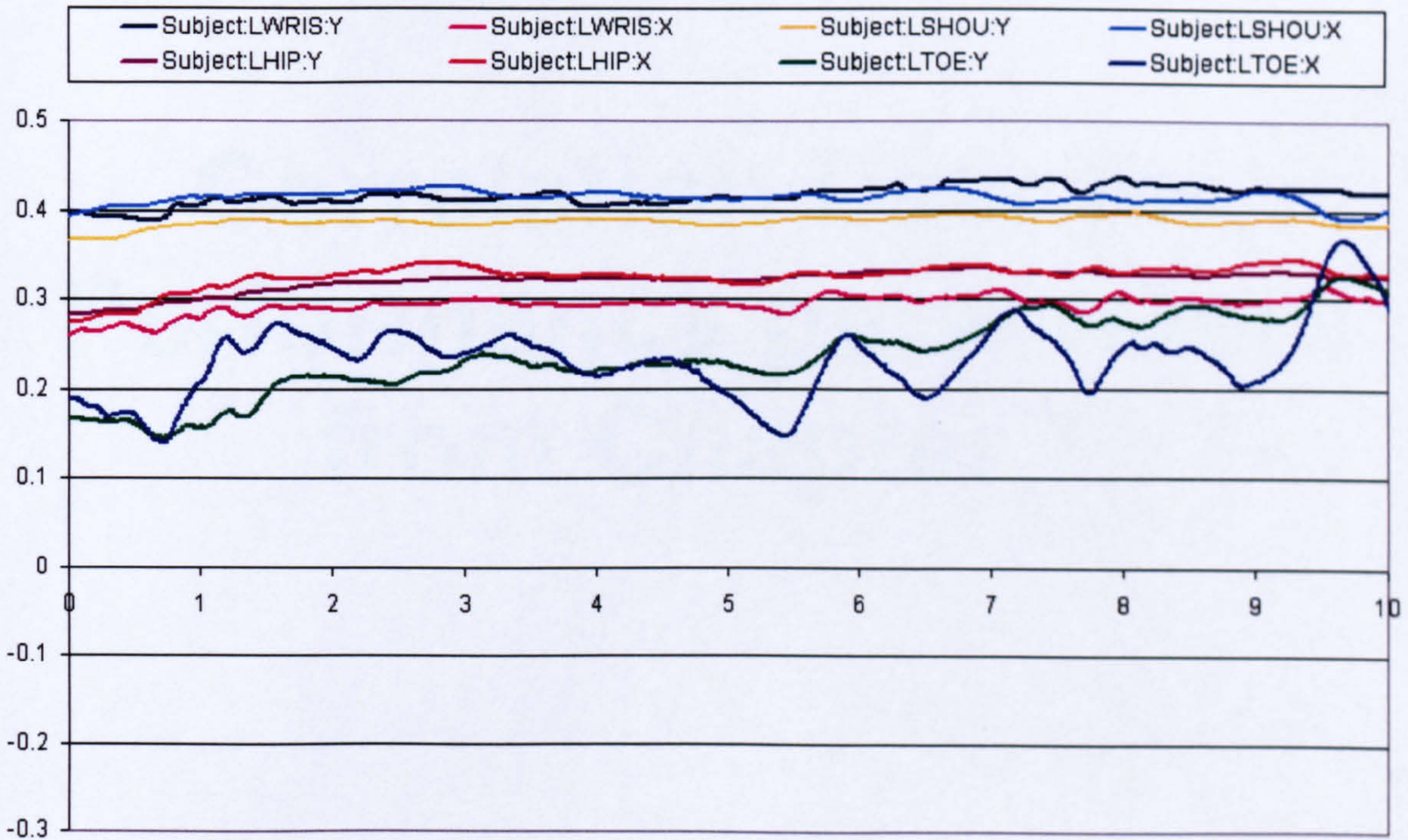


Figure E-8: Joint centre data for the rails 4 handstand.

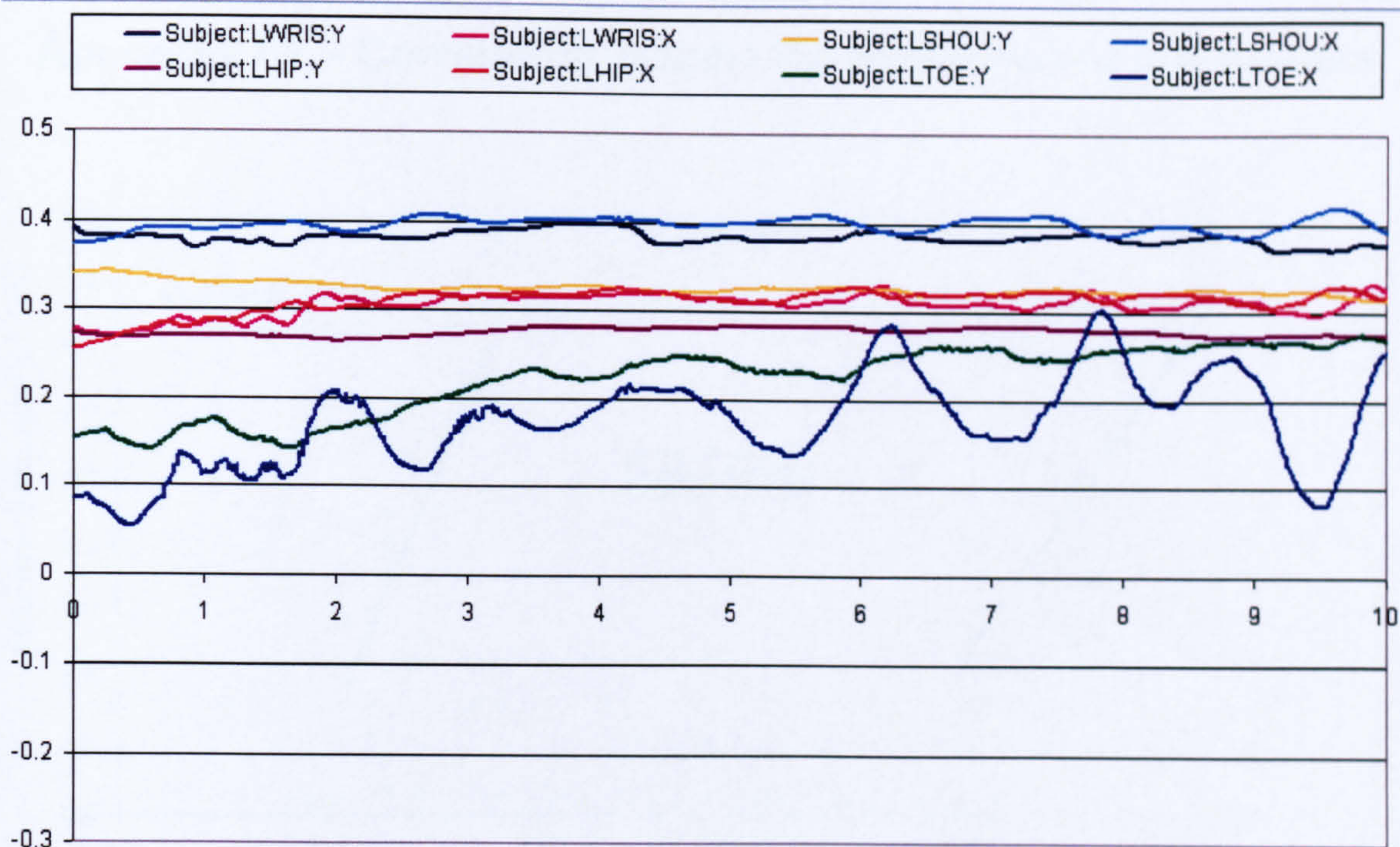


Figure E-9: Joint centre data for the rails 5 handstand.

Correlation Data for
Performance parameters
from Chapter 7

Appendix F

Correlation Data for Performance parameters from Chapter 7

Appendix F1 – Correlation graphs for performance parameters

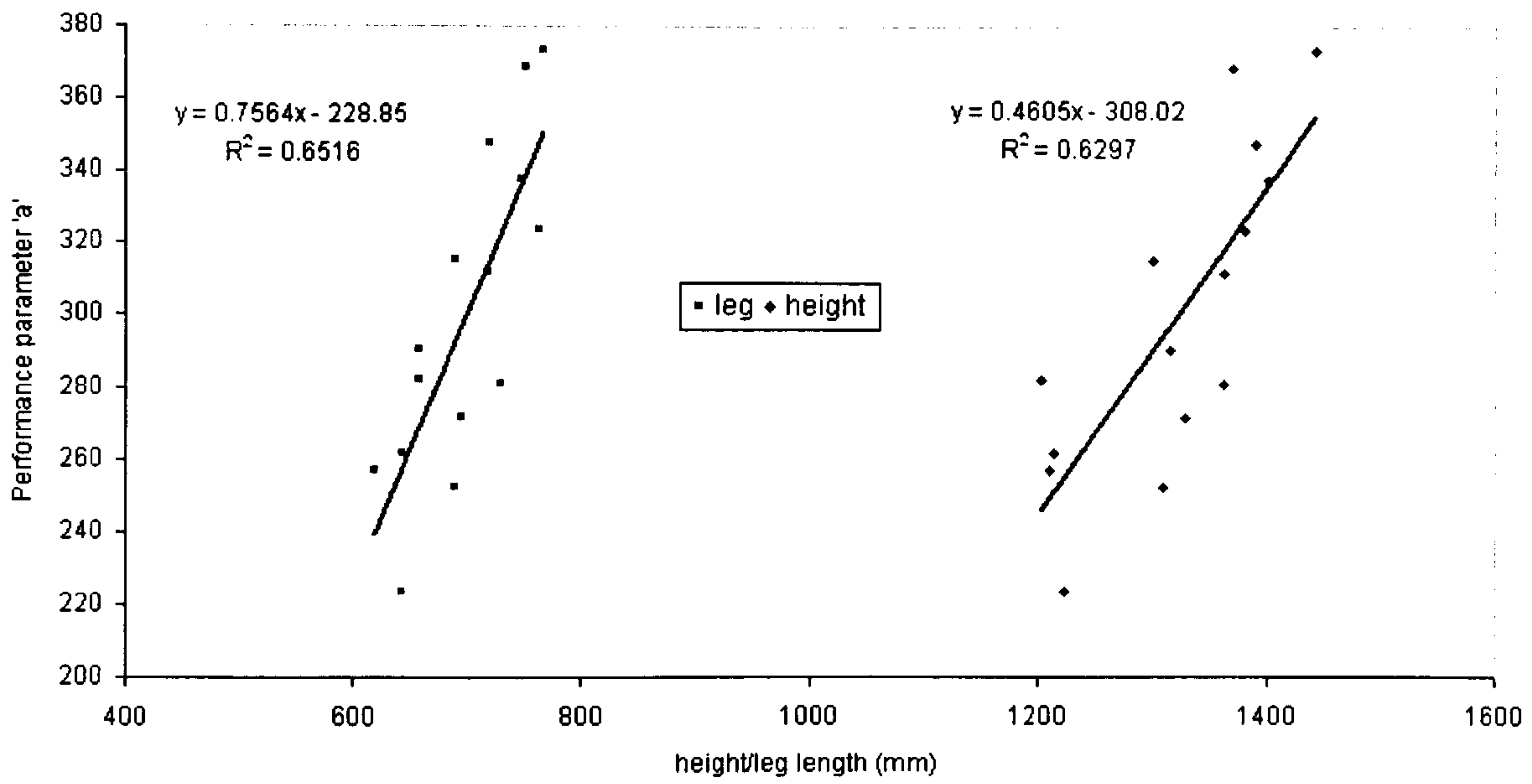


Figure F-1: Correlation graph for performance parameter 'a'.

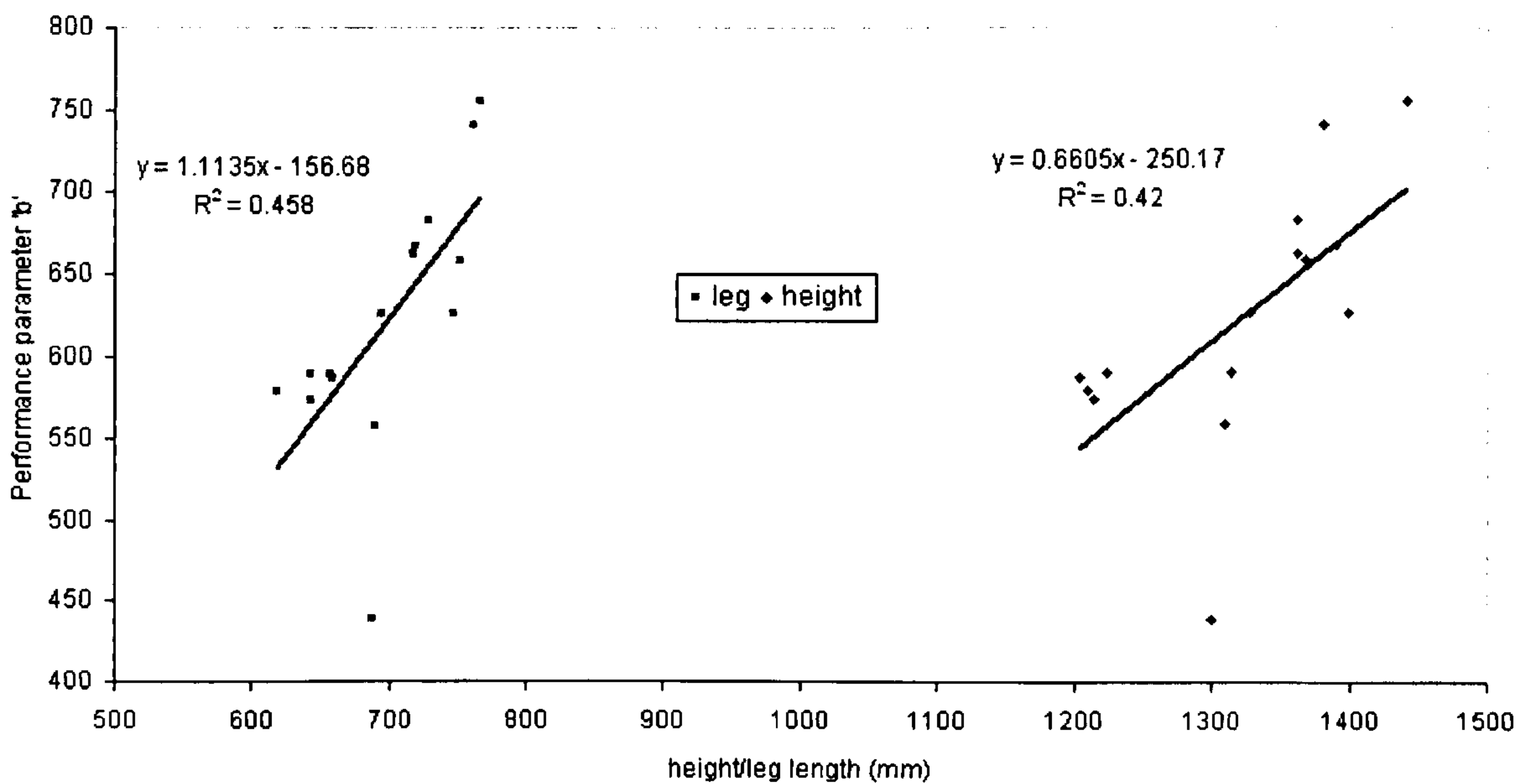


Figure F-2: Correlation graph for performance parameter 'b'.

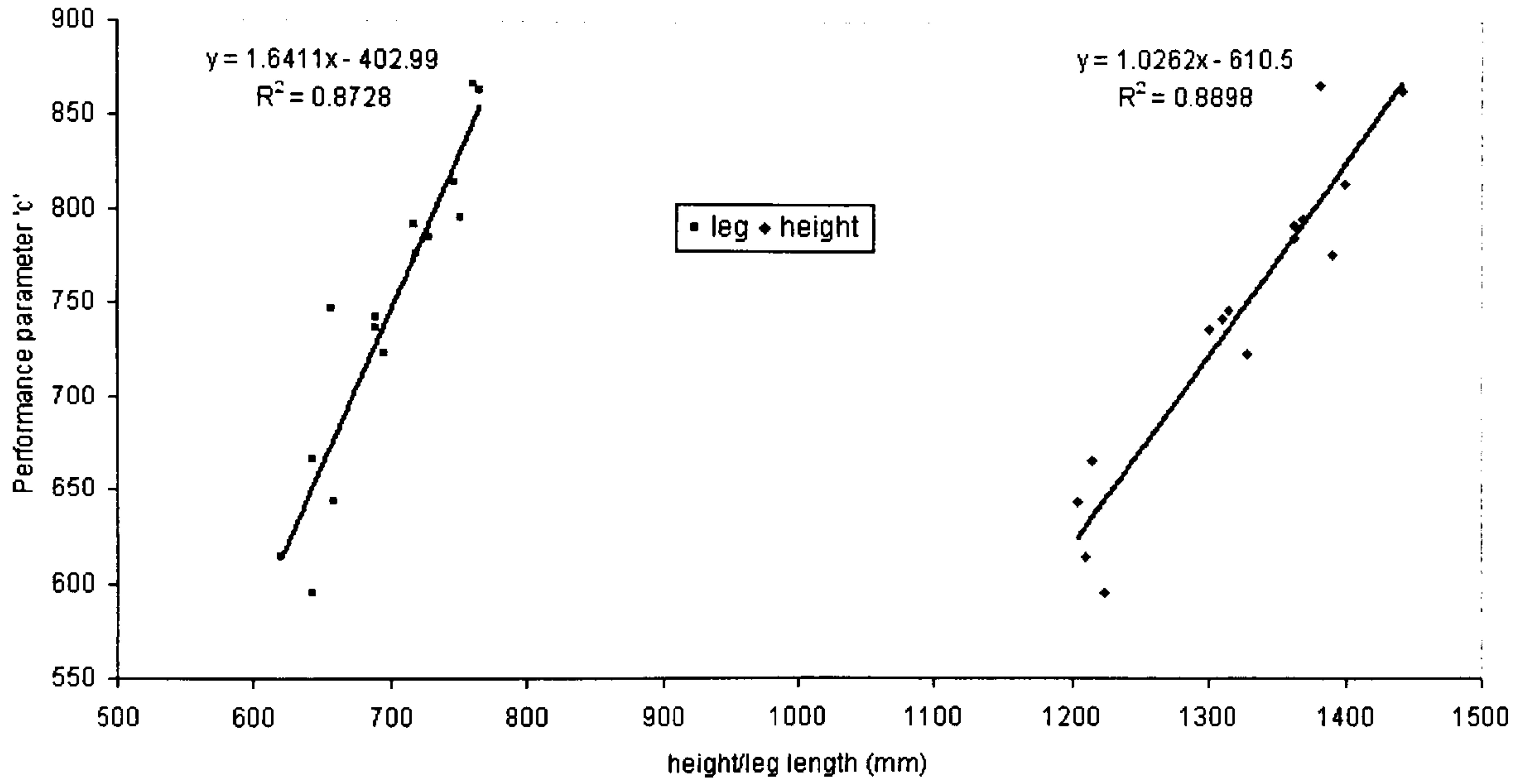


Figure F-3: Correlation graph for performance parameter 'c'.

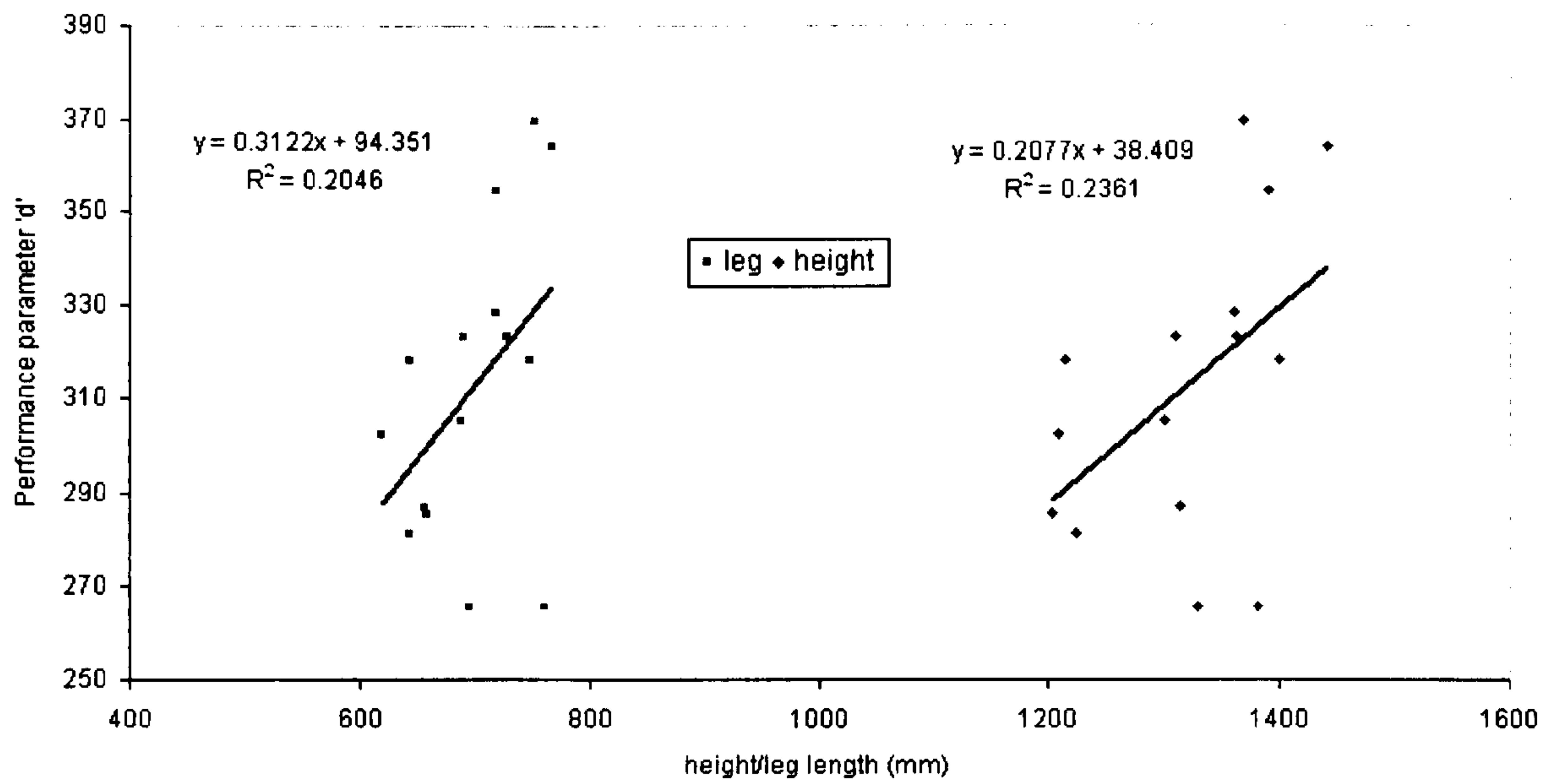


Figure F-4: Correlation graph for performance parameter 'd'.

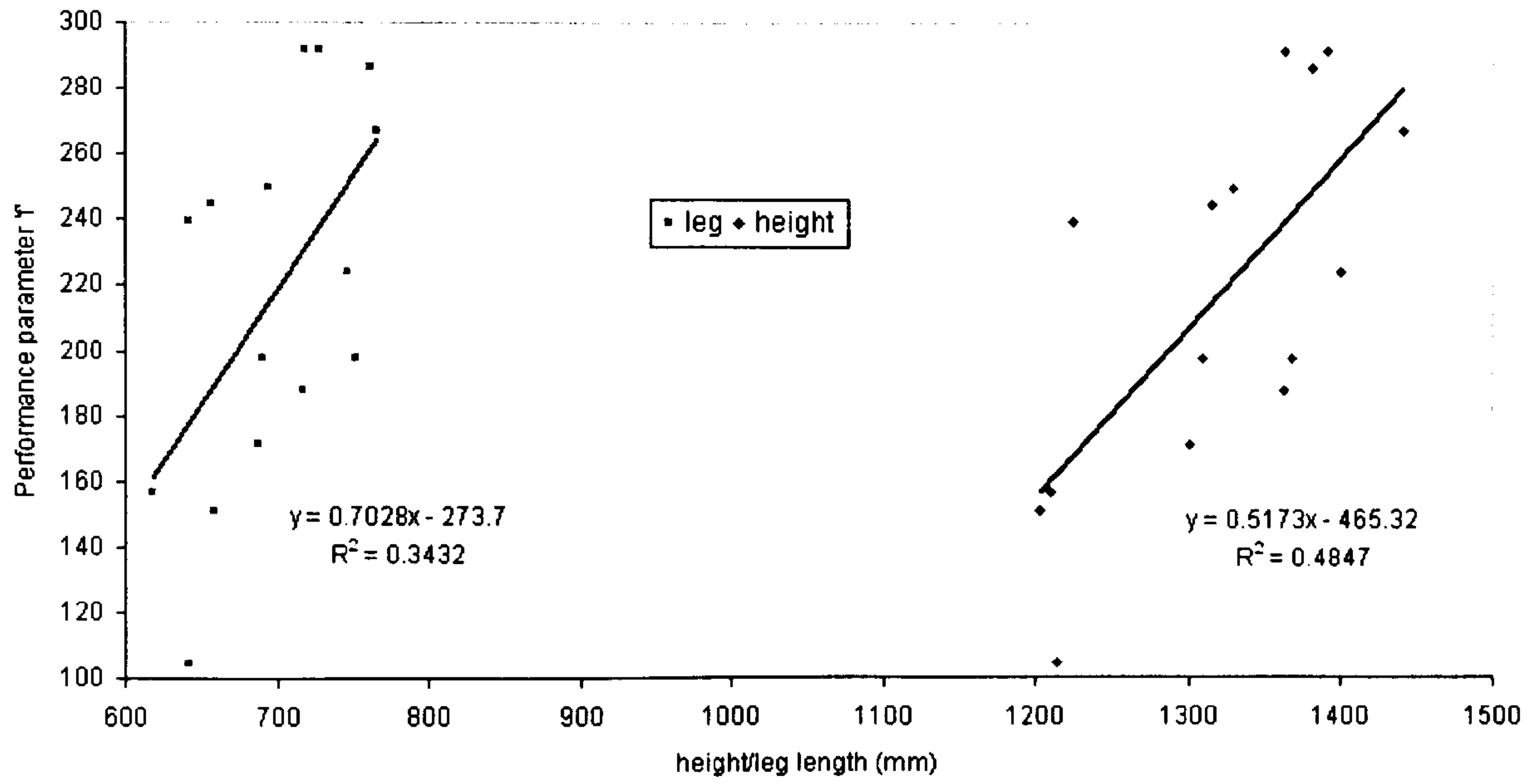


Figure F-5: Correlation graph for performance parameter 'f'.

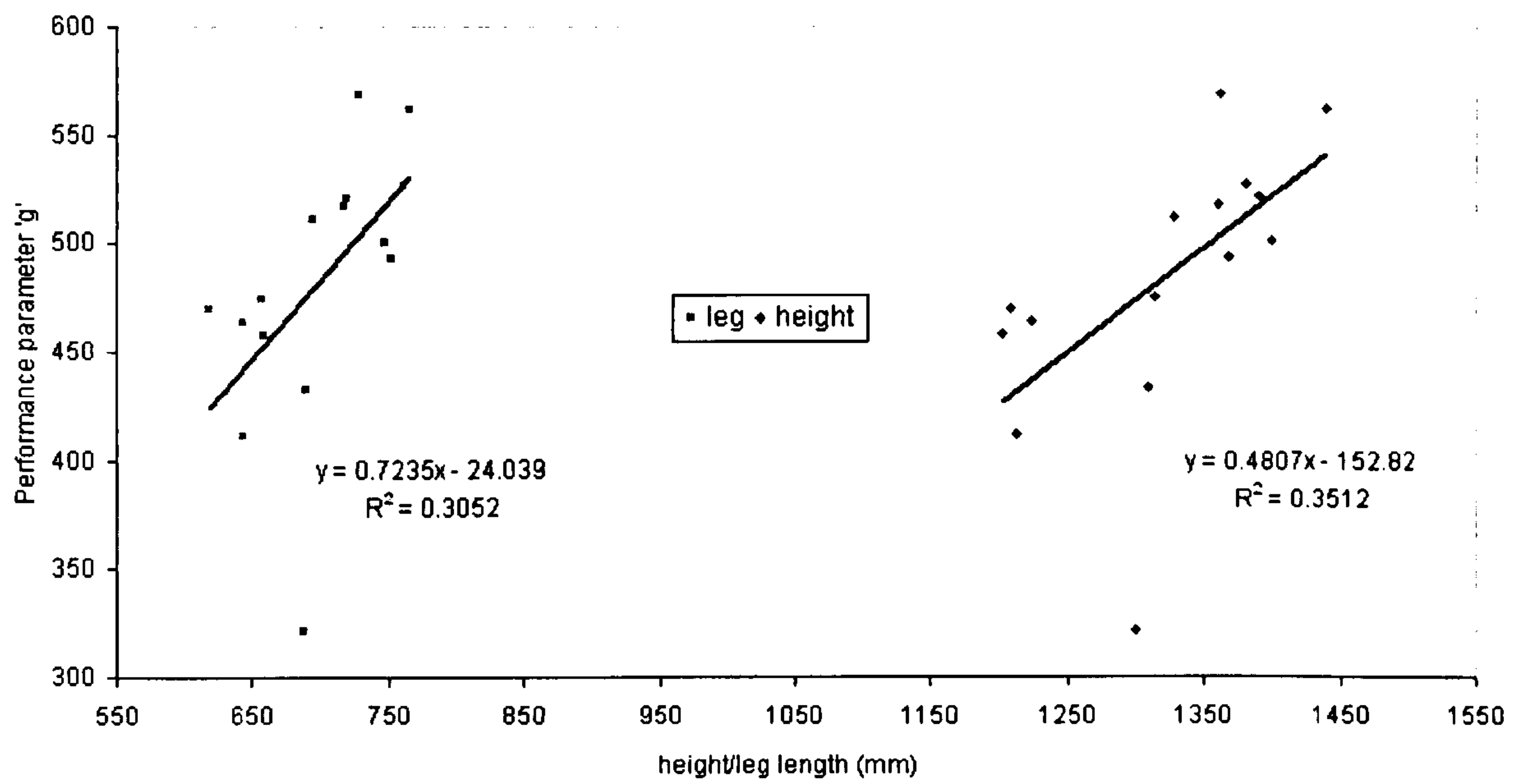


Figure F-6: Correlation graph for performance parameter 'g'.

Appendix G

Backward Handspring Data from Chapter 9

Appendix G1 – Backward handspring data
Appendix G2 – Discussion of data

Appendix G1 – Backward handspring data for all 8 gymnasts

Table G-1: Joint angles in degrees for the individual unsupported performance

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	133	140	134	130	150
Max height	123	125	125	136	148
Touch-down	130	140	137	156	152
Gymnast 2					
Takeoff	139	164	139	123	133
Max height	125	139	122	105	141
Touch-down	148	156	155	109	130
Gymnast 3					
Takeoff	138	150	129	130	141
Max height	131	145	110	124	160
Touch-down	133	141	139	120	123
Gymnast 4					
Takeoff	145	142	141	128	148
Max height	148	128	124	128	139
Touch-down	130	134	136	127	137
Gymnast 5					
Takeoff	151	141	140	126	142
Max height	127	119	116	110	133
Touch-down	138	154	166	107	101
Push-off	142	145	59	144	92
Landing	152	123	67	121	73
Gymnast 6					
Takeoff	139	134	141	132	133
Max height	135	141	121	112	144
Touch-down	135	141	142	124	116
Push-off	153	143	127	158	94
Landing	142	115	106	138	92
Gymnast 7					
Takeoff	137	139	135	144	152
Max height	164	129	116	136	131
Touch-down	142	129	119	133	146
Push-off	160	147	101	148	116
Landing	158	109	81	146	82
Gymnast 8					
Takeoff	148	137	146	124	159
Max height	133	129	123	121	161
Touch-down	132	133	143	137	153
Push-off	149	131	77	160	125
Landing	167	95	87	145	106

Table G-2: Joint angles in degrees for the individual performances over the training aid

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	138	163	130	134	157
Max height	126	121	114	127	169
Touch-down	129	143	179	158	125
Gymnast 2					
Takeoff	125	151	141	137	140
Max height	143	143	134	87	153
Touch-down	123	139	107	85	122
Gymnast 3					
Takeoff	150	158	126	132	140
Max height	148	137	116	129	125
Touch-down	132	151	163	172	106
Gymnast 4					
Takeoff	147	139	168	140	137
Max height	136	134	129	131	129
Touch-down	152	151	156	153	127
Gymnast 5					
Takeoff	150	140	146	145	143
Max height	136	131	125	133	145
Touch-down	138	129	150	162	141
Push-off	153	143	73	159	105
Landing	147	104	81	135	79
Gymnast 6					
Takeoff	161	143	148	130	122
Max height	140	131	128	109	126
Touch-down	149	157	154	147	129
Push-off	154	135	86	149	113
Landing	150	110	72	127	96
Gymnast 7					
Takeoff	137	144	145	131	160
Max height	145	128	115	110	141
Touch-down	141	142	162	136	123
Push-off	148	139	84	148	104
Landing	157	124	68	149	91
Gymnast 8					
Takeoff	166	148	153	117	125
Max height	140	139	123	118	138
Touch-down	137	148	156	144	138
Push-off	154	135	66	176	117
Landing	169	126	62	133	85

Table G-3: Differences between the joint angles for the individual unsupported performance and the performance over the training aid

	elbow	shoulder	hip	knee	ankle
Gymnast 1					
Takeoff	5	23	4	3	7
Max height	4	4	11	8	21
Touch-down	1	3	42	3	26
Gymnast 2					
Takeoff	14	13	2	14	7
Max height	18	5	12	19	13
Touch-down	25	17	48	24	8
Gymnast 3					
Takeoff	12	7	3	2	1
Max height	17	8	6	6	36
Touch-down	1	10	24	52	17
Gymnast 4					
Takeoff	2	4	27	12	11
Max height	11	5	5	3	10
Touch-down	23	18	20	27	10
Gymnast 5					
Takeoff	1	1	5	19	2
Max height	8	12	9	23	12
Touch-down	0	25	15	56	41
Push-off	11	1	14	15	14
Landing	5	18	15	14	7
Gymnast 6					
Takeoff	22	9	8	2	11
Max height	5	10	7	3	18
Touch-down	14	16	12	22	13
Push-off	1	8	41	9	20
Landing	8	5	33	11	4
Gymnast 7					
Takeoff	1	4	10	13	8
Max height	19	1	1	26	10
Touch-down	2	13	43	3	23
Push-off	12	8	17	0	12
Landing	1	15	13	3	9
Gymnast 8					
Takeoff	17	11	7	6	33
Max height	6	10	0	3	23
Touch-down	4	16	13	7	15
Push-off	5	4	11	16	8
Landing	2	31	25	12	21

Appendix G2 – Discussion of backward handspring data for all 8 gymnasts

Gymnasts 1, 2, 3, and 4

These gymnasts all felt more comfortable to perform a ‘walk-out’ backward handspring when performing over the training aid, as they felt this skill was easier to perform from standing than a standing two-footed backward handspring. This meant that two different techniques were used, during a single trial, as they performed an unsupported accelerator backward handspring, and a supported walk-out ‘floater’ backward handspring when supported using the training aid. Only limited comparisons could therefore be made for these gymnasts.

A ‘walk-out’ backward handspring involves splitting the legs as the hands make contact with the floor. It appears that this action can be performed either late once the hips have passed over the hands, or early before the hips get level with the hands. This is because the action of splitting the legs reduces the dynamic requirement of the backward handspring, permitting a low effort performance during the second phase of the skill.

Takeoff: During the takeoff phase, no real differences should be observed with the four ‘walk-out’ performances. Gymnast 1 had a greater shoulder angle when performing over the training aid, and this suggested that the gymnast was attempting to create more height than in the unsupported performance. This can be explained by a lack of confidence in performing over the training aid.

Gymnast 2 had straighter legs at takeoff which was a good indication of a positive drive back in the first phase of the skill and showed an improvement in this gymnast’s backward handspring as he had a tendency to push his knees forward on takeoff. His shoulder angle was also smaller, which was evidence that he was using a late shoulder action to increase the length of the skill. Further confirmation of an improvement in the skill was the fact that the performance over the training aid was greater in length than the unsupported performance (see Table 9.8).

Gymnast 3 has no obvious differences in her takeoff. Gymnast 4, had a greater hip angle during the supported performance. This too can be explained by the gymnast being concerned about colliding with the training aid, and so prematurely lifted her hips. This same gymnast also increased the angle at the knee, suggesting a more active backward direction in the takeoff.

Maximum height: At maximum height, gymnast 1 had a slightly smaller hip angle, and gymnast 2 had a slightly larger hip angle, but only in the magnitude of ten

degrees. This combined with the information that none of the four gymnasts had any large differences at the shoulder angle suggested that they all had a very similar body configuration during both the supported and unsupported first flights.

Touch-down: Gymnasts 1, 3 and 4 all had a larger hip and shoulder angle at touch-down, and gymnast 2 had a smaller hip and shoulder angle. This was due to all four gymnasts performing a walk-out backward handspring as discussed earlier in this section. From this information it was concluded that gymnast 2 did not feel confident performing over the training aid as he bent his arms on landing to reduce the impact and split his legs very early in order to get the first foot to the floor quickly. The other three gymnasts showed no real differences in the first half of the skill, but still chose to perform a walk-out backward handspring. From the data obtained, it appears that they would have been capable of performing an accelerator backward handspring safely over the training aid with exactly the same takeoff as they executed in their second performances.

Performance parameters: These gymnasts all performed a slightly higher skill over the training aid, which is accounted for by them performing the walk-out technique, as was discussed in Chapter 3. All of the backward handsprings over the training aid also had a slightly longer first phase, except gymnast 4 whose backward handspring was a very similar length. The sit height of gymnasts 1 and 2 remained almost unchanged, whereas gymnasts 3 and 4 did not sit quite as deep when using the training aid. All gymnasts except gymnast 3 sat back further into the skill when using the training aid which is classed as a good technique. It has already been identified that gymnast 3 appeared to be very conscious of 'clearing' the training aid, and reducing sit height and depth when performing over the training aid would be a factor in this.

Gymnast 5

Takeoff: The knees were pushed back to straighten the leg more during the supported performance as the gymnast attempted to increase the length of the skill. This is a positive effect as the unsupported skill was slightly loopy.

Maximum height: The shoulders were more open during the supported performance. This will be due to the length of the skill being increased in comparison with the unsupported skill.

Touch-down: Both the shoulders and hips were slightly more closed during this phase in the unsupported skill, and legs were much straighter. This suggested that the gymnast was pre-empting the landing more in the supported performance, which was a positive response.

Push-off: During this phase, the gymnast's hips remained more open during the supported performance. This suggested that she had prolonged the snap-down action and achieved more rotation in the first phase of the skill through good technique. Her arms were also straighter at this point than during an unsupported performance.

Landing: On landing, the shoulders of the gymnast were more closed, and the hips were more open. From the video, the supported backward handspring had a long first phase and a short second phase, which is in agreement with more open hips and closed shoulders as this is the resultant position of a dynamic second phase. During the unsupported performance the first and second phases had similar displacements.

Performance parameters: Gymnast 5 executed a slightly higher, but much longer performance over the training aid than on her own. She also sat lower and back further in her takeoff during the supported performance, making it an all-round better performance.

Gymnast 6

Takeoff: There were no large differences between the two performances except the gymnast had straighter arms and his shoulders were slightly more open during the unsupported performance.

Maximum height: No significant differences were measured during this phase of the performance.

Touch-down: At touch-down the gymnast had straighter elbows, a more open hip angle, straighter legs, and a more open shoulder angle during the supported performance. He was generally in a much better shape than during his unsupported performance.

Push-off: The main difference at push-off was that the gymnast had already started to close his hips. When watching the performances there was no real difference to be seen. However the difference in hip angle was due to a later push-off in the supported performance, which so long as it was not to the extent that it effects the dynamics of the second phase, would not be classed as poor technique.

Landing: On landing, the gymnast had a more closed hip angle, and a slightly smaller shoulder angle. It is probable that the gymnast started the snap-down action too early due to rushing to finish the skill over the training aid. There was, however, no observed difference in the dynamics of the two performances.

Performance parameters: Gymnast six performed a slightly longer and slightly higher skill when performing over the training aid: he sat a little lower, and not quite as far back during takeoff as he did in his own performance, but as stated earlier, there was no difference observed whilst watching the two performances.

Gymnast 7

Takeoff: During the takeoff phase of the supported backward handspring the gymnast had a more closed knee angle but a more open hip angle. This suggested that the gymnast pushed her knees forward during takeoff as she was conscious of the foam block behind her legs.

Maximum height: At maximum height the only notable difference was that the gymnast had more bent arms and legs during the unsupported performance, but the overall shape in the air was the same. The hip and shoulder angles were almost identical between the two performances.

Touch-down: The gymnast had more open hips and shoulders during the unsupported phase, which indicates a much better landing position than in the unsupported performance.

Push-off: As like gymnast 6, gymnast 7 began to close her hips early in the second phase of the supported performance.

Landing: As a consequence of the push-off, the gymnast landed with a more closed hip angle during the unsupported performance, and also had a more open shoulder angle during the same performance. This resulted in a less dynamic performance in the second phase of the supported skill in comparison to the unsupported skill. However, as her flight was the same for both performances, it is more likely that psychological factors determined the early snap down, rather than mechanical factors.

Performance parameters: As was identified above, the gymnast pushed her knees slightly forward during takeoff, and as described in Warren (2003) this produces a high, short backward handspring due to the takeoff angle and angular momentum involved in the performance. This was in agreement with the measurements taken on the two performances. Not only was the first phase of the unsupported skill higher and shorter, but she also did not sit down or back as far as during her unsupported takeoff. Although the supported backward handspring was performed safely, the flexing action of the knees in the takeoff lead to a technically poor performance.

Gymnast 8

Takeoff: The only difference between the two performances was that the shoulder angle was more open in the supported backward handspring.

Maximum height: The gymnast's shoulders remained in an open position during flight, resulting in a better arched shape during the flight in the supported performance.

Touch-down: Both shoulders and hips were more open on touch-down during the supported performance, and an awkward torso twist which was observed to occur during unsupported performances disappeared when performing over the training aid.

Push-off: The gymnast had slightly more closed hips during the push-off in the supported performance, but her knees were much straighter. The supported backward handspring did have less dynamic content in the second phase, but the hand landing was on matting which could have affected this.

Landing: On landing the gymnast had a more closed hip angle, but a more open shoulder angle during the supported performance, and slightly more bent knees were also observed. However, the performance was still safe, but just lacked some dynamic elements in the second phase.

Performance parameters: Gymnast 8 performed a marginally higher backward handspring, and did not sit down quite so far when performing over the training aid. The length of the first phase, and the length of the sit were almost identical for the two performances. Although this gymnast appeared to use less power in her backward handspring over the training aid, the skill became straight whereas before there was a twist in her torso. The skill was performed safely, although technically weak in the second phase.