



THE UNIVERSITY OF
NEWCASTLE
AUSTRALIA

Cervical Spine Sensorimotor Control
in Individuals with
Chronic Idiopathic Neck Pain

Rutger M.J. de Zoete

BSc(Physio), MSc

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy (Physiotherapy)

July 2018

School of Health Sciences, Faculty of Health and Medicine

The University of Newcastle

This is to certify that the thesis entitled *Cervical Spine Sensorimotor Control in Individuals with Chronic Idiopathic Neck Pain*, submitted in fulfilment of the requirements for the degree Doctor of Philosophy (Physiotherapy), is in a form ready for examination.

12 July 2018

Signature

Date

Rutger M. J. de Zoete

School of Health Sciences

Faculty of Health and Medicine

The University of Newcastle

DECLARATION

I hereby certify that the work embodied in this thesis is my own work, conducted under normal supervision.

This thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository**, subject to the provisions of the Copyright Act 1968.

**Unless an Embargo has been approved for a determined period.

I hereby certify that this thesis is in the form of a series of published papers of which I am a joint author. For each such work a written statement, endorsed by the other authors and the Faculty Assistant Dean (Research Teaching), attesting to my contribution to the joint work has been included.

12 July 2018

Rutger de Zoete _____

Signature

Date

ACKNOWLEDGEMENTS

This thesis is the result of a three-year adventure that I have enjoyed every day. I am very grateful for the opportunity I was given to complete my PhD at The University of Newcastle and would like to thank a number of people in particular.

Firstly, my principal supervisor Associate Professor Snodgrass, Suzanne, thank you for your exceptional guidance throughout my PhD candidature. Your ambition and resilience are inspiring, and I could not have wished for a better mentor. To my other supervisors, Doctor Osmotherly, Peter, and Professor Rivett, Darren, your input and feedback have been invaluable for my project. To the three of you, thank you for providing me with so many research and teaching opportunities and for supporting me during my project.

During my candidature I was awarded a PhD top-up scholarship through the Hunter Medical Research Institute (HMRI). Felicity and Michael Thomson, I am grateful for the support you have given me and would like to express my sincere gratitude for supporting early career researchers such as myself. To The University of Newcastle's Centre for Brain and Mental Health Research, thank you for supporting my project with two travel grants, allowing me to visit national and international conferences and further build my network.

This project gained strength from collaborating with researchers at different institutions. I would like to acknowledge the support of Doctor Julia Treleaven (The University of Queensland, Australia), Doctor Eythor Kristjansson (The University of Iceland, Iceland), and Professor Enrique Ferreira (Universidad Católica del Uruguay, Uruguay). Thank you for sharing your methodologies and

making testing and analysis software available for my studies, it has been a pleasure working with you. I am grateful to Jason Harris for his technical support in setting up our movement laboratory.

This project would not have been possible without the one-hundred participants who volunteered their time to visit our laboratory for assessments. I am so thankful for their help and it has been a pleasure meeting each of them. I would like to thank Mark Rothfield and the HMRI Research Register team for assistance in the recruitment of participants.

My time in Australia would not have been the same without three people by my side. To Nienke and Damian, thank you for your kindness and support, for listening to all my neck pain stories, and for all those hours on the tennis court. To Sophie, I am profoundly grateful for the support and love you have given me while completing my PhD. I am humbled by your ever-positive energy while encouraging me to work hard.

Lastly, there are only three people the final words of this section could be devoted to. To my sister, Marieke, thank you for the support and humour you have offered over the past three years. To my wonderful parents, Annemiek and Marco, thank you for believing in me, for your endless love and support, and for the many early-morning and late-night calls. Your words are always comforting and I envy your combined wisdom.

SUPERVISOR STATEMENT

I, Associate Professor Suzanne J. Snodgrass, attest that Research Higher Degree candidate Rutger M. J. de Zoete was the lead author of the following publications:

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2018). *Cervical Sensorimotor Control Does Not Change over Time and is Not Related to Chronic Idiopathic Neck Pain Characteristics: A Six-Month Longitudinal Observational Study. Under Review.*
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2018). No Differences between Individuals with Chronic Idiopathic Neck Pain and Healthy Individuals on Seven Cervical Sensorimotor Control Tests: A Case-Control Study. *Under Review.*
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (in press). Seven Cervical Sensorimotor Control Tests Measure Different Skills in Individuals with Chronic Idiopathic Neck Pain. *Brazilian Journal of Physical Therapy.*

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Farrell S.F., Snodgrass S.J. (2016). Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: A systematic review and meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 98:1257-71. doi: 10.1016/j.apmr.2016.09.121

12 July 2018

Suzanne Snodgrass _____

Signature

Date

PUBLICATIONS AND PRESENTATIONS INCLUDED AS PART OF THE THESIS

Papers Published and Submitted for Publication in Peer-Reviewed Scientific Journals

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2018). *Cervical Sensorimotor Control Does Not Change over Time and is Not Related to Chronic Idiopathic Neck Pain Characteristics: A Six-Month Longitudinal Observational Study. Under Review.*
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2018). No Differences between Individuals with Chronic Idiopathic Neck Pain and Healthy Individuals on Seven Cervical Sensorimotor Control Tests: A Case-Control Study. *Under Review.*
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (in press). Seven Cervical Sensorimotor Control Tests Measure Different Skills in Individuals with Chronic Idiopathic Neck Pain. *Brazilian Journal of Physical Therapy.*

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Farrell S.F., Snodgrass S.J. (2016). Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: A systematic review and meta-analysis. *Archives of Physical Medicine and Rehabilitation*, 98:1257-71. doi: 10.1016/j.apmr.2016.09.121

Abstracts Presented at Peer-Reviewed Scientific Conferences

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2018, April). Cervical Sensorimotor Control is Not Correlated with Neck Pain or Neck Disability in Individuals with Chronic Idiopathic Neck Pain. Poster presentation at the Australian Pain Society/New Zealand Pain Society Conference, Sydney, Australia.
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2017, December). No differences in cervical sensorimotor control between individuals with chronic idiopathic neck pain and healthy individuals. Platform presentation presented at the Sensorimotor Control Satellite Meeting of the Australasian Neuroscience Society, Sydney, Australia.
- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2017, November). Cervical spine sensorimotor control in individuals with chronic idiopathic neck pain. Platform presentation presented at The University of Newcastle Centre for Brain and Mental Health Research conference, Newcastle, Australia.

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Snodgrass S.J. (2017, October). Head Tilt Response: A Novel Method to Test Spatial Orientation in Individuals with Idiopathic Neck Pain. Platform presentation presented at the conference of the Australian Physiotherapy Association, Sydney, Australia.

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Farrell S.F., Snodgrass S.J. (2016, July). Sensorimotor control in individuals with idiopathic neck pain and healthy individuals: A systematic review and meta-analysis. Platform presentation presented at the quadrennial conference of the International Federation of Orthopaedic Manipulative Physical Therapists, Glasgow, Scotland. doi:10.1016/j.math.2016.05.041

- de Zoete R.M.J., Osmotherly P.G., Rivett D.A., Farrell S.F., Snodgrass S.J. (2015, October). Sensorimotor control in people with insidious onset neck pain and healthy individuals: a systematic review. Platform presentation presented at the biannual conference of the Australian Physiotherapy Association, Gold Coast, Australia. doi: 10.13140/RG.2.1.1810.8883

I warrant that I have obtained, where necessary, permission from the copyright owners to use any third-party copyright material reproduced in the thesis (e.g. questionnaires, artwork, unpublished letters), or to use any of my own published work (e.g. journal articles) in which the copyright is held by another party (e.g. publisher, co-author).

TABLE OF CONTENTS

DECLARATION	III
ACKNOWLEDGEMENTS	IV
SUPERVISOR STATEMENT	VI
PUBLICATIONS AND PRESENTATIONS INCLUDED AS PART OF THE THESIS	VIII
Papers Published and Submitted for Publication in Peer-Reviewed Scientific Journals	VIII
Abstracts Presented at Peer-Reviewed Scientific Conferences	X
TABLE OF CONTENTS	XIII
LIST OF TABLES	XVII
LIST OF FIGURES	XIX
ABSTRACT	XXX
Chapter 1 Introduction	1
1.1 Background	1
1.2 Sensorimotor Control and Chronic Neck Pain	4
1.3 Chronic Idiopathic Neck Pain	10
1.4 Rationale of the Thesis	12
Chapter 2 Literature Review	14
2.1 Overview	14
2.2 Aetiology of Neck Pain	16
2.3 Sensorimotor Control	19

2.4 Chronic Neck Pain and Cortical Changes.....	23
2.5 Neck Pain and Sensorimotor Control.....	27
2.6 Evaluation of Measurements of Cervical Sensorimotor Control	31
Chapter 3 Sensorimotor Control in Individuals with Idiopathic Neck Pain and Healthy Individuals: A Systematic Review and Meta-Analysis	41
3.1 Introduction	43
3.2 Methods	46
3.3 Results	50
3.4 Discussion.....	79
3.5 Conclusion	86
3.6 Appendices	87
Chapter 4 Seven Cervical Sensorimotor Control Tests Measure Different Skills in Individuals with Chronic Idiopathic Neck Pain	89
4.1 Introduction	91
4.2 Methods	94
4.3 Results	102
4.4 Discussion.....	109
4.5 Conclusions.....	114
Chapter 5 No Differences between Individuals with Chronic Idiopathic Neck Pain and Healthy Individuals on Seven Cervical Sensorimotor Control Tests: A Case-Control Study.....	115
5.1 Introduction	117
5.2 Methods	119

5.3 Results	127
5.4 Discussion.....	139
5.5 Conclusions.....	147
Chapter 6 Cervical Sensorimotor Control Does Not Change over Time and is Not Related to Chronic Idiopathic Neck Pain Characteristics: A Six-Month Longitudinal Observational Study	148
6.1 Introduction	150
6.2 Methods	152
6.3 Results	158
6.4 Discussion.....	166
6.5 Conclusion	174
Chapter 7 Further Exploration of Data	175
7.1 Introduction	175
7.2 Methods	182
7.3 Results	186
7.4 Discussion.....	196
7.5 Conclusion	202
Chapter 8 Summary and Conclusions	203
8.1 Summary of Study Findings	203
8.2 Limitations of Studies	210
8.3 Implications	213
8.4 Future Research Questions.....	216
8.5 Conclusions.....	219

Appendices	220
Appendix A: Statements from Co-Authors of (Published) Papers	221
Appendix B: Notification of Human Research Ethics Committee Approval Studies 2-4	229
Appendix C: Participant Recruitment Flyer Studies 2-4	235
Appendix D: Participant Information Statement Studies 2-4	237
Appendix E: Participant Consent Form Studies 2-4.....	241
Appendix F: Journal Publication Study 1	242
Appendix G: Cervical Sensorimotor Control Outcomes for Healthy Individuals and Individuals with Chronic Idiopathic Neck Pain	258
Appendix H: Cervical Sensorimotor Control Outcomes in Relation to Neck Pain Intensity and Neck Disability.....	272
References.....	328

LIST OF TABLES

Table 3.1. Methodological quality and risk of bias assessment of included studies.	54
Table 3.2. Summary of included studies.	61
Table 3.3 Methods to assess sensorimotor control.....	68
Table 3.4. Ranges for reported means of JPE and the number of included studies.	71
Table 3.5. Ranges for reported means of postural sway and the number of included studies.....	75
Table 4.1. Demographics of participants (n=50) with descriptive data for each test and test condition (mean, SD or median, IQR).	103
Table 4.2. Correlations between cervical sensorimotor control tests and test conditions in individuals with chronic idiopathic neck pain.	104
Table 4.3. Isolated factors (with labels) and their Eigen values after Promax oblique rotation.	105
Table 4.4. Cervical sensorimotor control test item loadings for each of the four factors.....	107
Table 5.1. Description of sensorimotor control tests used with participants with chronic idiopathic neck pain (n = 50) and healthy age and gender matched control participants (n = 50).	123
Table 5.2. Characteristics of participants with chronic idiopathic neck pain (n = 50) and health age and gender matched control participants (n = 50).....	128

Table 5.3. Outcomes of physical tests (range of motion and sensorimotor control test outcomes; median, IQR) for individuals with chronic idiopathic neck pain (n = 50) and healthy age and gender matched control participants (n = 50), with p-values for between group differences	130
Table 5.4. Correlations (Spearman’s rho) with p-values between cervical sensorimotor control test outcomes and pain (three recall periods) and disability in individuals with chronic idiopathic neck pain.	132
Table 5.5. Cut-off values suggesting poor performers, with proportions of poor performers within each group (chronic idiopathic neck pain, n=50, and healthy age and gender matched controls, n=50).....	138
Table 6.1. Baseline characteristics for individuals with chronic idiopathic neck pain and healthy individuals, with p-values for between group differences.	160
Table 6.2. Cervical range of motion and sensorimotor control outcomes for individuals with chronic idiopathic neck pain and healthy individuals, for all time points.	161

LIST OF FIGURES

Figure 1.1. Sensorimotor control and its subsystems	5
Figure 3.1. Flow of studies through the review.....	52
Figure 3.2. Significant difference ($p=0.04$) between medians (and IQRs) of pooled data for joint position error (JPE) to the neutral head position (NHP) in individuals with idiopathic neck pain and healthy individuals.	73
Figure 3.3. No significant differences between medians (and IQRs) for postural sway (eyes open: $p=0.16$, eyes closed: $p=0.30$) in individuals with idiopathic neck pain and healthy individuals.	77
Figure 4.1. Factor loading plot of all cervical sensorimotor control tests. Postural balance and head steadiness account for most of the variance across tests.	108
Figure 5.1. Distribution for all skewed outcomes with cut-off values (highest 10%) for 'poor performers'.	134
Figure 5.1 cont. Distribution for all skewed outcomes with cut-off values (highest 10%) for 'poor performers'.	136
Figure 6.1. Flow of participants through the study	159
Figure 7.1. Relationship between balance with eyes open (BalanceEO, sway path in mm) and neck pain intensity (VAS4weeks: four-week recall, VAS 0-100mm).	188
Figure 7.2. Changes in neck pain intensity (VASnow: current pain, VAS 0-100mm) for each individual participant at each time point (TIME: 1, baseline; 2, four-week follow-up; 3, eight-week follow-up; 4, six-month follow-up). ...	190

Figure 7.3. Changes in neck pain intensity (VAS7days: seven-day recall, VAS 0-100mm) for each individual participant at each time point (TIME: 1, baseline; 2, four-week follow-up; 3, eight-week follow-up; 4, six-month follow-up).	191
Figure 7.4. Changes in neck pain intensity (VAS4weeks: four-week recall, VAS 0-100mm) for each individual participant at each time point (TIME: 1, baseline; 2, four-week follow-up; 3, eight-week follow-up; 4, six-month follow-up).	192
Figure 7.5. Changes in neck disability (NDI: 0-50) for each individual participant at each time point (TIME: 1, baseline; 2, four-week follow-up; 3, eight-week follow-up; 4, six-month follow-up).	193
Figure G.1. Changes in conventional joint position error (JPEconv, error in deg) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	258
Figure G.2. Changes in joint position error torsion (JPEtorsion, error in deg) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	259
Figure G.3. Changes in balance with eyes open (BalanceEO, sway path in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	260
Figure G.4. Changes in balance with eyes closed (BalanceEC, sway path in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	261

Figure G.5. Changes in balance with torsion and eyes open
 (BalanceTorsionEO, sway path in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.
262

Figure G.6. Changes in balance with torsion and eyes closed
 (BalanceTorsionEC, sway path in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.
263

Figure G.7. Changes in subjective visual vertical (SVV, error in deg) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....264

Figure G.8. Changes in head tilt response (HTR, error in deg) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....265

Figure G.9. Changes in the easy condition of The Fly® (FlyA, error in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....266

Figure G.10. Changes in the medium condition of The Fly® (FlyB, error in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....267

Figure G.11. Changes in the difficult condition of The Fly® (FlyC, error in mm) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....268

Figure G.12. Changes in the low load condition of the head steadiness test (HSlow, velocity in mm/s) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	269
Figure G.13. Changes in the high load condition of the head steadiness test (HShigh, velocity in mm/s) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.	270
Figure G.14. Changes in smooth pursuit neck torsion (SPNT, gain) for each individual participant (healthy controls, left; individuals with idiopathic neck pain, right) at each time point.....	271
Figure H.1. Relationship between conventional joint position error and pain intensity (VASnow: current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	272
Figure H.2. Relationship between conventional joint position error and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	273
Figure H.3. Relationship between conventional joint position error and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	274
Figure H.4. Relationship between conventional joint position error and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	275
Figure H.5. Relationship between joint position error torsion and pain intensity (VASnow: current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	276

Figure H.6. Relationship between joint position error torsion and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	277
Figure H.7. Relationship between joint position error torsion and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	278
Figure H.8. Relationship between joint position error torsion and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	279
Figure H.9. Relationship between balance with eyes open and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	280
Figure H.10. Relationship between balance with eyes open and pain intensity (VAS7days, seven-day recall period, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	281
Figure H.11. Relationship between balance with eyes open and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	282
Figure H.12. Relationship between balance with eyes open and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	283
Figure H.13. Relationship between balance with eyes closed and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	284

Figure H.14. Relationship between balance with eyes closed and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.285

Figure H.15. Relationship between balance with eyes closed and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.286

Figure H.16. Relationship between balance with eyes closed and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.287

Figure H.17. Relationship between balance with torsion and eyes open and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.288

Figure H.18. Relationship between balance with and torsion eyes open and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time289

Figure H.19. Relationship between balance with torsion and eyes open and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.290

Figure H.20. Relationship between balance with torsion and eyes open and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.291

Figure H.21. Relationship between balance with torsion and eyes closed and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.292

Figure H.22. Relationship between balance with torsion and eyes closed and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.293

Figure H.23. Relationship between balance with torsion and eyes closed and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.294

Figure H.24. Relationship between balance with torsion and eyes closed and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.295

Figure H.25. Relationship between subjective visual vertical and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.296

Figure H.26. Relationship between subjective visual vertical and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.297

Figure H.27. Relationship between subjective visual vertical and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.298

Figure H.28. Relationship between subjective visual vertical and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.299

Figure H.29. Relationship between head tilt response and pain intensity for (VASnow, current pain, VAS 0-100mm) 50 individuals with chronic idiopathic neck pain, without regard to time.300

Figure H.30. Relationship between head tilt response and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time	301
Figure H.31. Relationship between head tilt response and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	302
Figure H.32. Relationship between head tilt response and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	303
Figure H.33. Relationship between the easy condition of The Fly® and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	304
Figure H.34. Relationship between the easy condition of The Fly® and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	305
Figure H.35. Relationship between the easy condition of The Fly® and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	306
Figure H.36. Relationship between the easy condition of The Fly® and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	307
Figure H.37. Relationship between the medium condition of The Fly® and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	308

Figure H.38. Relationship between the medium condition of The Fly® and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.309

Figure H.39. Relationship between the medium condition of The Fly® and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.310

Figure H.40. Relationship between the medium condition of The Fly® and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.311

Figure H.41. Relationship between the difficult condition of The Fly® and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.312

Figure H.42. Relationship between the difficult condition of The Fly® and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.313

Figure H.43. Relationship between the difficult condition of The Fly® and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.314

Figure H.44. Relationship between the difficult condition of The Fly® and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time315

Figure H.45. Relationship between the low load condition of head steadiness and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.316

Figure H.46. Relationship between the low load condition of head steadiness and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.317

Figure H.47. Relationship between the low load condition of head steadiness and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.318

Figure H.48. Relationship between the low load condition of head steadiness and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.319

Figure H.49. Relationship between the high load condition of head steadiness and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.320

Figure H.50. Relationship between the high load condition of head steadiness and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.321

Figure H.51. Relationship between the high load condition of head steadiness and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.322

Figure H.52. Relationship between the high load condition of head steadiness and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.323

Figure H.53. Relationship between smooth pursuit neck torsion and pain intensity (VASnow, current pain, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.324

Figure H.54. Relationship between smooth pursuit neck torsion and pain intensity (VAS7days, seven-day recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	325
Figure H.55. Relationship between smooth pursuit neck torsion and pain intensity (VAS4weeks, four-week recall, VAS 0-100mm) for 50 individuals with chronic idiopathic neck pain, without regard to time.	326
Figure H.56. Relationship between smooth pursuit neck torsion and neck disability (NDI, neck disability index, 0-50) for 50 individuals with chronic idiopathic neck pain, without regard to time.	327

ABSTRACT

The aim of this thesis was to investigate the clinical relevance of cervical sensorimotor control in individuals with chronic idiopathic neck pain. Sensorimotor control has been defined as all the afferent and efferent information streams, as well as the central integration components contributing to joint stability, and recent research has suggested that cervical sensorimotor control might be disturbed in individuals with neck pain. However, current evidence is ambiguous and different studies with varying study designs and source populations report inconsistent findings. This body of work, reporting the findings of four studies, addresses this issue by investigating cervical sensorimotor control in a homogenous sample of individuals with chronic idiopathic neck pain.

Chapter 1 provides a brief introduction to neck pain and sensorimotor control and presents the research question for this thesis: (1) what is the most useful test or combination of tests for assessing cervical sensorimotor control in individuals with idiopathic neck pain, and (2) is chronic idiopathic neck pain associated with cervical sensorimotor control? Chapter 2 discusses literature on cervical sensorimotor control in individuals with neck pain in more detail, and further discusses what tests measurements have been used to assess cervical sensorimotor control.

Chapter 3 reports the findings of Study 1; a systematic review of the literature with meta-analysis that identified six tests that have been used to assess cervical sensorimotor control in individuals with idiopathic neck pain. These tests included measurements of joint position error, postural balance,

subjective visual vertical, smooth pursuit neck torsion, head steadiness, and The Fly®. One other outcome measure, head tilt response, although not described in this population, was deemed relevant for individuals with idiopathic neck pain. Meta-analysis demonstrated a statistically significant difference between pooled means for joint position error, however the actual magnitude of the difference was not considered clinically meaningful. In further meta-analyses for postural balance, no differences were found between individuals with chronic idiopathic neck pain and healthy individuals.

Chapter 4 reports the findings of Study 2, which tested whether seven cervical sensorimotor control tests measure the same, or different, skills. The study found that different tests did not cluster together in factor analysis, indicating that all tests measure distinct skills and potentially unique characteristics of cervical sensorimotor control. Two tests, postural balance and head steadiness, were found to explain a large proportion of the variance across the variables. This study suggests that clinically not one test or test battery can be recommended, and arguably clinicians have to perform all tests to adequately assess cervical sensorimotor control or nominate which aspect of cervical sensorimotor control they are examining.

Chapter 5 presents Study 3 and reports a case-control study comparing outcomes of seven cervical sensorimotor control tests in 50 individuals with chronic idiopathic neck pain and 50 sex and age matched healthy individuals. With groups being similar in terms of sex, age, BMI and physical activity levels, no differences were found for any of the cervical sensorimotor control tests. This suggests that these tests may not be clinically useful to discriminate between individuals with chronic idiopathic neck pain and healthy individuals. Additionally,

correlations between cervical sensorimotor control outcomes and neck pain intensity and neck disability were weak at best, further questioning the clinical meaningfulness of these tests.

Chapter 6 reports the findings of Study 4, which investigated whether changes in cervical sensorimotor control occur over time in individuals with chronic idiopathic neck pain, and what factors are associated with changes in cervical sensorimotor control. Only half of the sensorimotor control outcomes significantly changed over a six-month period. It was further found that changes in cervical sensorimotor control outcomes were not associated with characteristics of neck pain, including neck pain intensity, neck pain duration, and neck disability. Other factors, such as sex, age, BMI, and physical activity level, were not associated with changes in cervical sensorimotor control. This suggests that clinically, cervical sensorimotor control might not be a relevant assessment for individuals with chronic idiopathic neck pain.

This thesis contributes to the understanding of the relevance of cervical sensorimotor control in individuals with chronic idiopathic neck pain. Based on inconsistent findings in recent literature, the clinical meaningfulness of cervical sensorimotor control has been questioned. From the current studies demonstrating that (1) seven tests appear to measure unique aspects that may address different characteristics of cervical sensorimotor control, (2) none of these tests discriminate between individuals with chronic idiopathic neck pain and healthy individuals, and (3) cervical sensorimotor control outcomes are not associated with characteristics of neck pain, it is suggested that cervical sensorimotor control may not be useful in the clinical assessment of individuals with chronic idiopathic neck pain.