

**Submaximal Torque Control at the
Shoulder in Young, Healthy Adults: The
Effects of Dual Tasking, Fatigue and
Taping**

Thomas Frank Adams

A thesis submitted to Auckland University of
Technology in fulfilment of the requirements for the
degree of Doctor of Philosophy (PhD)

2026

School of Clinical Sciences

Table of Contents

Chapter 1: Introduction	23
1.1 Background	23
1.2 Statement of the Problem	31
1.3 Significance of this Doctoral Research	33
1.4 Thesis Presentation	34
Chapter 2: Literature Review	36
2.1 Introduction.....	36
2.2 Literature Search.....	36
2.2.1 Search Terms.....	37
2.3 The Mobile Glenohumeral Joint.....	37
2.4 The Sensorimotor System	38
2.5 Sensory Innervation of the Glenohumeral Joint	39
2.6 Sensorimotor Integration.....	41
2.7 Motor Output	43
2.8 Summary	44
2.9 Submaximal Torque Control	45
2.9.1 Introduction.....	45
2.9.2 Torque Control Tasks	46
2.9.3 Torque steadiness.....	48
2.9.4 Torque matching accuracy.....	52
2.10 Findings from Clinical Studies	54
2.11 Torque Control at the Shoulder	56

2.11.1	Study characteristics	57
2.11.2	Study reporting quality	61
2.11.3	Summary of study findings.....	65
2.12	Dual Tasking	71
2.12.1	Introduction.....	71
2.12.2	Dual Task Paradigms in the Musculoskeletal Context	72
2.12.3	Dual Tasking and Torque Control.....	73
2.12.4	Summary	74
2.13	Fatigue	74
2.13.1	Introduction.....	74
2.13.2	Fatigue in the Musculoskeletal Context.....	75
2.13.3	Fatigue and torque control	77
2.13.4	Summary	80
2.14	Taping	80
2.14.1	Introduction.....	80
2.14.2	Taping in the Musculoskeletal Context.....	81
2.14.3	Taping and Torque Control.....	82
2.14.4	Summary	83
2.15	Overall Summary	84
	Introduction to Experimental Chapters	86
	Chapter 3: The Effects of Dual Tasking on Submaximal Torque Control at the Shoulder.....	89
3.1	Introduction.....	89
3.1.1	Aims.....	95

3.2	Methodological Considerations.....	95
3.2.1	Isometric peak torque	96
3.2.2	Tasks	97
3.2.3	Target torque levels	98
3.2.4	Shoulder testing position.....	99
3.2.5	Limb Dominance	100
3.2.6	Cutaneous sensory influences.....	101
3.2.7	Visual gain.....	102
3.2.8	Learning Effect	103
3.2.9	Dual Tasking	104
3.3	Methods.....	110
3.3.1	Study Design	110
3.3.2	Ethical Approval	110
3.3.3	Sample Size Calculation	110
3.3.4	Participant Recruitment.....	111
3.3.5	Inclusion & Exclusion Criteria	112
3.3.6	Participant Characteristics	112
3.3.7	Experimental Set-up	113
3.3.8	Warm-up and Shoulder Peak Torque.....	113
3.3.9	Order of Testing	115
3.3.10	Isometric Torque Matching Task	115
3.3.11	Isometric Torque Tracking Task	117
3.3.12	Visual Stroop Task.....	118

3.3.13	Cognitive-Motor Dual-Task	119
3.3.14	Data Sampling.....	119
3.3.15	Data Processing.....	119
3.3.16	Dependent Variables	120
3.3.17	Dual Task Effect.....	121
3.3.18	Statistical Analyses	122
3.4	Results	123
3.4.1	Torque Matching Task	124
3.4.2	Torque Tracking Task.....	127
3.4.3	Visual Stroop Task.....	127
3.4.4	Dual Task Effect.....	128
3.4.5	Family-wise Error	129
3.5	Discussion	129
3.6	Conclusion & Future Research Directions	138

**Chapter 4: The Effect of Local Muscle Fatigue on Submaximal Torque Control
at the Shoulder** **141**

4.1	Introduction.....	141
4.1.1	Aims.....	145
4.2	Methodological Considerations.....	145
4.2.1	Common Considerations	145
4.2.2	Torque control and Visual feedback	146
4.2.3	Contraction type and intensity	148
4.2.4	Measurement of fatigue	151
4.2.5	Fatigue duration	152

4.2.6	Task selection	153
4.3	Methods.....	155
4.3.1	Study Design.....	155
4.3.2	Ethical Approval	155
4.3.3	Sample Size Calculation	155
4.3.4	Participant Recruitment.....	156
4.3.5	Inclusion/Exclusion Criteria.....	157
4.3.6	Participant Characteristics	157
4.3.7	Experimental Set-up	158
4.3.8	Warm-up and Shoulder Peak Torque.....	158
4.3.9	Torque Matching Task	158
4.3.10	Fatigue Protocol	159
4.3.11	Data Sampling.....	160
4.3.12	Data Processing.....	160
4.3.13	Dependent Variables	160
4.3.14	Statistical Analyses	161
4.4	Results	162
4.4.1	Fatigue Task.....	163
4.4.2	Torque Steadiness.....	164
4.4.3	Torque Matching Accuracy with Visual Feedback	164
4.4.4	Torque Matching Accuracy without Visual Feedback	164
4.4.5	Family-wise Error	165
4.5	Discussion	165

4.6	Conclusion & Future Research Directions	175
Chapter 5: The Effect of Shoulder Taping on Submaximal Torque Control at the Shoulder..... 178		
5.1	Introduction.....	178
5.1.1	Aims.....	182
5.2	Methodological Considerations.....	182
5.2.1	Common Methodologies	182
5.2.2	Rigid vs elastic tape	183
5.2.3	Taping technique.....	184
5.2.4	Use of a comparator	185
5.2.5	Washout Period.....	187
5.2.6	Summary	188
5.3	Methods.....	188
5.3.1	Study Design	188
5.3.2	Ethical Approval	188
5.3.3	Sample Size Calculation	189
5.3.4	Participant Recruitment.....	190
5.3.5	Inclusion/Exclusion Criteria.....	190
5.3.6	Participant Characteristics	191
5.3.7	Randomisation, Allocation Concealment and Blinding.....	192
5.3.8	Experimental Set-up	192
5.3.9	Warm-up and Shoulder Peak Torque.....	192
5.3.10	Torque Matching Task	193
5.3.11	Torque Tracking Task.....	193

5.3.12	Taping Application.....	194
5.3.13	Data sampling	195
5.3.14	Data Processing.....	196
5.3.15	Dependent Variables	196
5.3.16	Statistical Analyses	197
5.4	Results	197
5.4.1	Torque Steadiness.....	199
5.4.2	Torque Matching Accuracy	200
5.4.3	Torque Tracking Task.....	202
5.4.4	Family-wise Error	202
5.5	Discussion	202
5.6	Conclusion & Future Recommendations.....	207
Chapter 6: Summary & Conclusions		210
6.1	Introduction.....	210
6.2	Key Study Findings	211
6.2.1	Dual Tasking	211
6.2.2	Fatigue	214
6.2.3	Taping	216
6.2.4	Summary and Synthesis.....	218
6.3	Implications for Clinical Practice	222
6.4	Limitations	224
6.5	Implications for Future Research.....	227
6.6	Conclusion.....	229

References	232
Appendices	304

Abstract

The shoulder is a highly mobile joint, particularly the glenohumeral joint, which sacrifices articular stability for increased mobility. To compensate, the joint relies on the complex actions of muscles, especially the rotator cuff, to provide functional stability. The sensorimotor system integrates peripheral sensory feedback, central processing and efferent muscle output to ensure coordinated muscle activity, maintaining joint stability. Much of the research on shoulder sensorimotor control has focused on proprioception and almost exclusively on joint position sense and movement appreciation, with far less attention to torque control. Studies of torque control could offer insight into sensorimotor control under conditions that may pose an injury risk. The aim of this research was to investigate submaximal torque control at the shoulder in healthy young adults under conditions of dual tasking, fatigue and shoulder taping.

Three experimental studies were undertaken. The first, an observational cross-sectional study, investigated dual tasking and submaximal torque control of the shoulder internal and external rotators. The addition of a visual Stroop choice reaction task resulted in a dual task effect, with significant decreases in torque accuracy and steadiness during torque matching and tracking tasks. The second study, also of repeated measures design, examined the effects of an intermittent, duty-cycled, isometric fatiguing protocol on torque control in young healthy adults. Despite noticeable fatigue, torque matching accuracy and steadiness did not significantly differ between conditions. In the final study, a randomised crossover trial, participants performed shoulder torque matching and tracking tasks with and without a common shoulder taping technique. Taping had no significant effect on torque control.

The main conclusions of this research were fourfold. 1) Cognitive dual-tasking impairs the ability of healthy individuals to match submaximal target torques and maintain steady torque output, suggesting the need for further research into motor-cognitive dual tasking in injury prevention and rehabilitation. 2) An intermittent isometric fatigue protocol did not significantly affect torque control in healthy young adults. However, applying this protocol to individuals with shoulder injuries and sensorimotor deficits might yield different results, offering important clinical insights. 3) A commonly used taping technique for shoulder injury prevention did not impact torque control meaningfully in healthy individuals. Similar to the fatigue findings, the effects of taping might differ in individuals with impaired sensorimotor control due to injury. 4) The studies used the same shoulder position and target torque, limiting the generalisability to other levels of torque or shoulder positions. Future research should explore the effects of varying target torque levels and other shoulder positions relevant to potential injury.

List of Abbreviations

ACL = Anterior cruciate ligament

ACJ = Acromioclavicular joint

AE = Absolute error

ADL = Activity of daily living

ACC = Accident and Compensation Corporation

CNS = Central nervous system

CT = Critical torque

CE = Constant error

CV = Coefficient of variation

EMG = Electromyography

ER = External rotation

GHJ = Glenohumeral joint

GTO = Golgi tendon organ

IR = Internal rotation

JPS = Joint position sense

KT = Kinesiology tape

MVC = Maximum voluntary contraction

PE = Percentage error

RMS = Root mean square

ROM = Range of motion

RT = Reaction time

SD = Standard deviation

SLAP = Superior labrum anterior to posterior

TMT = Torque matching task

TTT = Torque tracking task

VE = Variable error

VST = Visual Stroop task

WST = Wilcoxon signed-rank tests

Glossary

Dual Task Effect – This is the change in performance of a task from when it is performed on its own as a single task to when it is performed in conjunction with a secondary task under a dual task paradigm. The change can be negative or positive dependent on whether the performance of the task improves or deteriorates.

Dual Task Interference – Refers to the relative change in performance associated with dual tasking and encompasses the dual task effect of both tasks.

Joint Position Sense – Joint position sense (JPS) refers to one's ability to accurately ascertain the position of a joint in space. This can be via active or passive joint repositioning tasks. In an active task, an individual attempts to actively either reproduce a previously presented ipsilateral joint position/angle or match a position/angle in a contralateral limb. In a passive task, the individual attempts to recognise when the joint is passively positioned to a previously presented position/angle or match the position/angle of a contralateral limb.

Kinaesthesia – Kinaesthesia is the ability to recognise movement within a limb. This proprioceptive sense is most commonly assessed via threshold to detection of passive movement, whereby an individual is required to indicate the first point at which they sense a joint or limb is moved passively, whilst other sources of feedback such as vision and tactile stimuli are suppressed.

Sensorimotor control – The term sensorimotor control is used to describe the conscious and subconscious control of movement. It comprises the continuous integration of peripheral afferent stimuli, central nervous system processing, motor planning and motor execution. It includes neuromuscular control, which is a term used to describe the combination of the nervous and muscular systems in the control

of muscle force. Throughout this thesis, sensorimotor control is the preferred term as it encompasses all components of the system.

Torque control – Torque control refers to one's ability to control muscular force output acting across a joint and includes measures such as torque steadiness and torque matching accuracy. Throughout the literature, torque control and force control are used interchangeably, whereas in almost all cases, the correct term is torque, as force is being produced across a rotational axis of a peripheral joint. Hence torque control will be used as the preferred term throughout this thesis.

Torque matching accuracy – This refers to an individual's ability to match a presented target torque value, typically as a percentage of the individual's predetermined maximum voluntary isometric contraction and is associated with the proprioceptive sense of force. This is commonly recorded as root mean square, constant or absolute error. Torque matching tasks are usually performed ipsilaterally within the same limb and muscle group, although contralateral paradigms may require an individual to match a torque produced in an opposite limb. This research investigates ipsilateral torque matching tasks.

Torque steadiness – This represents how much a produced torque fluctuates around a mean produced torque and is typically a magnitude variable with measures of standard deviation and/or coefficient of variation of torque. Temporal measures of steadiness over time may also be investigated via sample entropy calculations although this research is primarily concerned with magnitude variables.

Task Trade Off – This function is the observation of changes in task performance relative to changes in performance of a simultaneous secondary task and represents inherent subjective task prioritisation by the individual performing the tasks.

List of Tables

Table 1. Literature search terms.....	37
Table 2. Study characteristics for studies on shoulder torque control	59
Table 3. Reporting of AXIS items for shoulder torque control studies	62
Table 4. Study variables and method of measurement	121
Table 5. Baseline characteristics across all participants, n=20 (<i>data presented as mean \pm one standard deviation, or as number/proportion as a percentage</i>).....	124
Table 6. Torque control and visual Stroop task variables under single and dual task conditions	125
Table 7. Baseline characteristics across all participants, n=20 (<i>data presented as mean \pm one standard deviation, or as number/proportion as a percentage</i>).....	163
Table 8. Participant shoulder internal rotation MVC and modified Borg scores by condition/task	164
Table 9. Baseline characteristics across all participants, n=20 (<i>data presented as mean \pm one standard deviation, or as number/proportion as a percentage</i>).....	199
Table 10 Participant characteristics by sequence (<i>data presented as mean \pm one standard deviation, or as number/proportion as a percentage</i>)	199
Table 11. A summary of the dependent variables for the <i>internal</i> rotation torque matching task (<i>data presented as mean \pm one standard deviation, or as median and interquartile range</i>)	201
Table 12. A summary of the dependent variables for the <i>external</i> rotation torque matching task (<i>data presented as median and interquartile range; *denotes a statistically significant finding</i>).....	201
Table 13. A summary of the dependent variables for torque tracking task (<i>data presented as median and interquartile range</i>).....	202

List of Figures

Figure 1. The distribution of Type I and II mechanoreceptors in the glenohumeral capsule [<i>reproduced from Witherspoon et al. (2014) with permission</i>]	40
Figure 2. Shoulder proprioceptive pathways [<i>reproduced from Ager et al. (2017) with permission</i>]	41
Figure 3. Centrally mediated sensorimotor integration [<i>adapted from work by Bays & Wolpert (2007)</i>]	42
Figure 4. Visual representation of torque steadiness (SD)	49
Figure 5. Visual representation of torque matching accuracy (RMS). The shaded area represents the difference between the participant's produced torque (magenta line) and the target torque (black line).	54
Figure 6. Participant Set Up & Custom Wrist Attachment (Close Up)	114
Figure 7. Data collection process	115
Figure 8. Example of a 35% MVC torque matching task incl. window for torque control variables calculation (<i>x-axis represents time [secs]; y-axis represents torque [Nm]; SD=standard deviation, RMS=root mean square; Solid horizontal line represents the 35% MVC target</i>)	117
Figure 9. Example of a participant torque tracking task trial (<i>x-axis represents time [secs]; y-axis represents torque [Nm]; the red line is the target torque line; the blue line is the participant's generated torque</i>)	118
Figure 10. A box and whisker plot showing torque steadiness (SD) for shoulder internal and external rotation torque during isometric torque matching tasks at 35% MVC, when performed as a single task and with the addition of a visual Stroop task (<i>IR=internal rotation; ER=external rotation; S=single task; D=Dual task</i>). Note: lower values represent greater torque steadiness.	126
Figure 11. A box and whisker plot showing torque accuracy (RMS) for shoulder internal and external rotation torque during isometric torque matching tasks at 35%	

MVC, when performed as a single task and with the addition of a visual Stroop task (*IR=internal rotation; ER=external rotation; S=single task; D=dual task*). *Note: lower RMS value represents greater accuracy.* 127

Figure 12. A box and whisker plot showing torque accuracy (RMS) during an isometric torque tracking task using the shoulder internal and external rotators when performed as a single task and with a combined visual Stroop task. *Note: lower RMS value represents greater accuracy.* 128

Figure 13. Visual Stroop task performance as a single task and with the addition of the torque tracking task. Panel A (left) a box and whisker plot showing participant response reaction time; Panel B (right) a bar chart showing participant response accuracy rate..... 128

Figure 14. An example of a participant 35% MVC torque matching trial (*y-axis represents torque [Nm], x-axis represents time [seconds]; black line represents the target torque line, the purple line is the participant's torque; the left curve is with visual feedback, the right is without visual feedback*). 159

Figure 15. Box and Whisker plot torque steadiness (SD) for the 35% MVC torque matching task by fatigue condition (pre- and post-fatigue protocol). Panel A shows the results with visual feedback, and Panel B without visual feedback (Means and SD shown). *Note: lower SD represents steadier torque.* 164

Figure 16. Box and Whisker plot showing torque matching accuracy (RMS Error) for the 35% MVC torque matching task by fatigue condition (pre- and post-fatigue protocol). Panel A shows the results with visual feedback, and Panel B without visual feedback (medians and interquartile ranges shown). *Note: lower RMS values reflect greater accuracy.* 165

Figure 17. An example of taping for scapula position [*taken from Kneeshaw (2002) with permission*] 184

Figure 18. An example of taping for GHJ stability [*taken from Bradley et al. (2009) with permission*] 185

Figure 19. The pattern of shoulder taping was as follows; 1 and 3 were sites for non-woven tape and then rigid anchors (region 2 was not used in this study); 4-6 represent the overlapping strips of rigid tape, before anchors were re-applied at 1 and 3; finally, the shoulder was reinforced with elastic bandage [*taken with permission from Weerakkody & Allen (2017)*]..... 196

Figure 20. Participant flowchart as per CONSORT guidelines (Dwan et al., 2019) 198

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

Signed:

Date: 13th April 2026

Acknowledgements

The American philosopher Ralph Waldo Emerson once said, *“It’s not the destination but the journey”*, and it’s been one hell of a journey. I would never have made it without the help and generosity of numerous people through this long process in seeing me reach my destination.

First and foremost, to my PhD supervisors Professor Peter McNair and Associate Professor David Rice, your mentorship over the past several years has been invaluable. Thank you for your patience, for your insightful comments, for your encouragement of my critical thinking, and for the hours of work put into reading and providing feedback along the way. Peter, your critical mind and attention to detail have helped me to grow in confidence in quantitative research immeasurably. The breadth of my reading thanks to your nudging me down rabbit holes, has taken me to many places I didn’t think I’d go, and I’m a far better researcher as a result. David, your extensive knowledge, and willingness to help has always been very much appreciated.

I would like to extend my thanks to the New Zealand Manual Physiotherapists Association and Sports and Exercise Physiotherapists New Zealand whose education fund grants supported my research and were gratefully received. Thanks are also owed to Pam Oliver for her assistance with proof-reading of this thesis.

I’m incredibly fortunate to have many friends and colleagues who have provided me with support in many different forms. I’d like to thank Julia Hill and Niki Saywell for their unwavering encouragement and commitment to ‘get me over the line’. That celebration lunch can’t come soon enough! To my non-physio, non-academic friends, thanks for always keeping me grounded and reminding me that sometimes a cold beer, rolling some dice or dropping a fishing line are perfect antidotes to long hours of study.

This PhD journey has been long and at times arduous. The unexpected loss of my father was quickly followed by the global COVID-19 pandemic. Needless to say, the culmination of these events took their toll on me. Throughout it all my wife Karen and children, Matilda and Sebastian, have been my absolute rock. Tilds and Basti, I have watched you grow into fine young adults over this process, but you keep me young and are a constant source of amusement. Karen, there aren't the words to describe just how thankful and lucky I am that you have stuck with me over these years. I lost count of the number of times I heard those words 'you've got this', but I think I finally have! I can never thank you enough, although I am looking forward to providing the same support for you on your very own PhD journey.

Finally, I owe a huge debt of gratitude to my parents Frank and Rosemary. I am extremely grateful for their support over many years. I would never have had the success in my life if it were not for the opportunities afforded to me by your love and support. To my father in particular, I am eternally thankful for your push to strive to achieve what I am capable of. The completion of this thesis is therefore bittersweet, as I can't celebrate with you, but I got there in the end Dad!

Use of Artificial Intelligence (AI)

AI assistance (Claude, Anthropic) was used during the amendment process to help organise and sequence examiner feedback, identify relevant sections of the thesis, and structure my approach to each amendment. All analytical thinking, synthesis, and written content remains my own (see Appendix F for the full AI interaction protocol used).

Ethics Approval

Ethical approval for the research presented in this thesis was provided by the New Zealand Health and Disability Ethics Committee (HDEC) (reference 21/NTB/98) and Auckland University of Technology Ethics Committee (AUTEK) (reference 21/348).

I'd like to thank all of the participants who generously gave their time, making this research possible.

Chapter 1: Introduction

1.1 Background

The evolution of the human shoulder girdle has resulted in an inherently mobile glenohumeral joint (GHJ) that allows for a large range of motion (ROM) and an array of possible movements across the planes of motion (Arias-Martorell, 2019). However, this mobility comes with a compromise in mechanical stability and the GHJ is predictably the most frequently dislocated joint in the body. Incidence rates of GHJ dislocation in the general population have been reported between 8 and 25 per 100 000 person years (Nordqvist & Petersson, 1995; Zacchilli & Owens, 2010); within a young athletic population, Owens et al. (2009) reported an incidence of 0.12 per 1000 hours of athlete exposure. Aside from dislocation, shoulder injury rates are also high in populations such as overhead athletes, with previously reported injury rates ranging between 18 and 61% (Asker et al., 2018; Cools et al., 2021).

Chronically impaired shoulder function is a significant sequela to shoulder injury. For example, following dislocation the risk of recurrent instability within two years is documented as high as 55.7% (Robinson et al., 2006). This recurrence leads to further healthcare cost and additional lost time for work, sport, and activities of daily living (ADLs). In New Zealand between 2019 and 2023, an average of 7,499 new cases of shoulder dislocation were recorded annually by ACC, at an average cost of \$88,256,354 per annum (personal communication with ACC Analytics and Reporting Senior Analyst, 2024). Previous studies have attempted to identify and recommend methods to mitigate shoulder injury risk (Asker et al., 2018; Liaghat et al., 2023; A. A. Wright et al., 2021). Despite significant research and economic input, injury prevention strategies do not appear to be particularly effective (A. A. Wright et al., 2021).

Several studies have investigated shoulder biomechanics in relation to injury risk. Subtle increases in GHJ translation occur during active movement at different velocities (Matsui et al., 2018). Three-dimensional modelling has shown that GHJ stability during elevation is almost exclusively due to co-ordinated muscle activity (Favre et al., 2012). Thus, it has been suggested that deficits in sensorimotor control may result in reduced stability (Favre et al., 2012; Warner et al., 1996). Appropriate control of shoulder muscle force, in particular the rotator cuff, is needed to mitigate GHJ translations and maintain the centralisation of the humeral head on the glenoid fossa (Magarey & Jones, 2003).

Despite the widely reported importance of the role of dynamic stability at the shoulder, studies of shoulder biomechanics remain somewhat limited (Favre et al., 2012), with most studies focused on peak muscle forces, muscle force vectors and muscle activation patterns (see Akhtar et al., 2021 for a recent review). During sporting activity of the upper limb, high torques occur at the shoulder, with the wind-up and deceleration phases of throwing being one of the most injurious athletic movements (Escamilla & Andrews, 2009). Given their importance in GHJ stability, studies have examined rotator cuff muscle activation during different types of activity. Dependent on the sport and style of throw, electromyographic (EMG) activity of the rotator cuff muscles has been reported to be between 26% and 113% of maximum voluntary contraction (MVC) (Escamilla & Andrews, 2009). During ADLs such as walking and donning/doffing a shirt, rotator cuff activity has been reported at lower values ranging between 12% and 25% (Gurney et al., 2016). Relatively low levels of rotator cuff muscle activation of between 28% and 37% have also been shown in response to external perturbations at the shoulder (Day et al., 2012).

Collectively, these findings place the primary operational demand of the dynamic stabilisers within a submaximal torque range, in which discharge rate modulation, rather than additional motor unit recruitment, has been demonstrated to govern

torque output (Enoka & Duchateau, 2017). Although studies directly examining sensorimotor demand across torque ranges are limited, proprioceptive deficits following glenohumeral instability or in the presence of pain, appear most functionally significant during controlled, low-load tasks (Ager et al., 2020; J. A. Fox et al., 2024; Lubiawski et al., 2019), supporting the notion that sensorimotor precision is a governing constraint in this torque range. In particular, accurate and steady torque production is required for coordinated rotator cuff activity to stabilise the GHJ against perturbing forces during fast repetitive movements such as throwing or sustained overhead work, placing demands on precision, co-ordination, fine motor control, and task-specific skill that are necessary for task performance and reduced injury risk.

Muscle torque control incorporates the ability to accurately match a target torque, as well as measures of torque variability, such as torque steadiness (Duchateau & Enoka, 2011; Enoka & Farina, 2021; Farina & Negro, 2015; Pethick, Clark, et al., 2022). Fluctuations in muscle torque signals are measured via magnitude variables of torque steadiness including the standard deviation (SD) and coefficient of variation (CV) over a given epoch (Enoka et al., 2003; Galganski et al., 1993; Santos et al., 2016; Slifkin & Newell, 1999). These measures represent the deviation from a fixed-point in a time series (Pethick, Clark, et al., 2022; Slifkin & Newell, 1999). Relatedly, a different measure of torque control is matching accuracy which relates to how accurately a produced torque matches a given target. A commonly used variable in the measurement of torque matching accuracy is RMS error (Kiyama et al., 2014; Magni et al., 2021; Perraton et al., 2017; Rice et al., 2015; Telianidis et al., 2014; Troussel et al., 2018; S. H. Ward et al., 2019). As the name implies, RMS error is the square root of the mean of the square of the differences between the target and output torque. It is expressed in the same units as the output variable (Nm).

The physiological mechanisms underlying these measures are well established in motor control literature. Torque steadiness is primarily determined by the slow

common oscillations in motor unit discharge rates which arise from shared synaptic input to motor neurons, which influences motor unit recruitment patterns and discharge rates (Dideriksen et al., 2012; Farina & Negro, 2015). This reflects the stability of descending neural drive with changes in steadiness indicating alterations in the coordination of motor output such as motor unit synchronisation and recruitment variability (Pethick et al., 2021). Contractile properties of motor units, number of motor units, and their recruitment thresholds such as increased motor unit firing rate variability, changes in recruitment threshold and differing size of motor units recruitment also influence torque steadiness (Farina & Negro, 2015; Tracy et al., 2005). This mechanistic basis makes measures of torque steadiness sensitive to factors that influence these physiological mechanisms. For example, torque steadiness has been demonstrated to be sensitive to motor unit synchronisation and common synaptic input changes due to ageing (Castronovo et al., 2018; Oomen & van Dieën, 2017); fatigue (Pethick & Tallent, 2022); and injury (Pethick, Clark, et al., 2022). Similarly, concurrent cognitive tasks performed with a motor task, have been demonstrated to influence torque steadiness due to increased variability in common synaptic inputs (H. M. Pereira et al., 2018, 2019).

In contrast, torque matching accuracy reflects the integration of peripheral mechanoreceptor afferent signals and centrally generated effort signals via corollary discharge to accurately reproduce a presented target torque (Luu et al., 2011; Proske & Allen, 2019). Assessments of matching accuracy are therefore typically performed in the absence of visual feedback, isolating the proprioceptive contribution to sense of force rather than visual sensory acuity. As both peripheral sensory feedback and central motor command contribute to the sense of force, changes in proprioceptive feedback or alterations in sensory processing may affect matching accuracy (Ghai et al., 2023; Riemann & Lephart, 2002b). For example, torque matching accuracy has been shown to be improved in the presence of taping, an

intervention proposed to improve proprioceptive acuity via increase input from stimulation of peripheral mechanoreceptors (Ghai et al., 2023). Comparably, visuomotor dual tasking has been demonstrated to reduce torque matching accuracy as the concurrent visual cognitive task competes with attentional resources required for the matching task (Cruz-Montecinos et al., 2018).

Torque steadiness and matching accuracy represent complementary but dissociable indices of torque control and the sensorimotor system. Whilst both depend on shared neural substrates (including sensorimotor integration processes, descending cortical drive, and efferent output) steadiness reflects the stability of common synaptic input to the motor neuron pool, whereas accuracy reflects the fidelity of the sense of force in calibrating output against a target.

In healthy uninjured cohorts, torque control has previously been associated with functional performance in a range of tasks including manual dexterity, standing balance, and walking performance (Enoka & Farina, 2021). For example, torque steadiness of the calf muscles is associated with standing balance in a cohort of 13 young males and females (28 \pm 4yrs) (Mello et al., 2013); pinch and grip torque steadiness are more strongly associated with functional peg board tasks than strength measures across women across differing age groups (18-36, n=11; 40-60yrs, n=17; >65yrs, n=17) (Marmon et al., 2011). These results suggest torque steadiness in healthy populations is relevant across multiple domains requiring motor co-ordination including fine motor control, balance and gait. In injured populations, the importance of torque control has also been established. For example, research suggests that subclinical neurophysiological changes can persist following concussion, manifesting as impaired sensorimotor control that leaves them vulnerable to future injury (Chmielewski et al., 2021). At the knee, quadriceps force control deficits, specifically impaired force steadiness, persist following anterior cruciate ligament (ACL) reconstruction and contribute to impaired sensorimotor

control strategies and abnormal kinematics that elevate the risk of subsequent injury or decreased joint health (Spencer et al., 2020; S. H. Ward et al., 2019).

Matching a single static target torque is a commonly used approach for examining torque control. Torque matching tasks are typically performed ipsilaterally, whereby the same limb generates and attempts to match a target torque (e.g. Rice et al., 2015; Skurvydas et al., 2011; Vieluf et al., 2017). Employing more complex tasks involving multi limb/joint movement makes studying torque output constructs a challenge due to potential confounding external/environmental influences on resultant torque control fluctuations (Furness et al., 1977). A compromise may be to use a variable target torque trace that requires a participant to modify their torque as they track the continually changing target trace, typically via a sinusoidal pattern. Tracking tasks include compensatory, pursuit and preview tasks (R. Jones, 1999). Pursuit tasks present current output and target simultaneously, whereas compensatory tasks differ in that they present only the difference between the target and the output. Preview tracking presents a variable target torque in advance, allowing participants to plan their response before producing torque to match the displayed target path. This type of tracking task has been proposed to have the greatest parallel with everyday function (R. Jones, 1999).

In the majority of the literature, submaximal levels of torque are used as the target torque. Submaximal torque control measures are particularly relevant for shoulder function, as the rotator cuff operates predominantly at submaximal intensities during both activities of daily living and athletic movements (Escamilla & Andrews, 2009; Gurney et al., 2016). This makes measures of steadiness and accuracy at submaximal intensities ecologically valid for understanding shoulder sensorimotor control and potentially more functionally relevant than maximal strength testing alone.

In recent decades, researchers have explored the importance of torque control at various joints, most notably the knee (Clark & Pethick, 2022). Deficits in measures of torque control have also been demonstrated after joint injury in the upper and lower limb as presented in a recent review (Pethick, Clark, et al., 2022). However, despite its proposed importance for GHJ stability, much less is known about torque control at the shoulder (Maenhout et al., 2012).

A handful of studies have explored shoulder torque control in injured populations (e.g. Bandholm et al. 2006; Zanca et al. 2010; Saccol et al. 2014), with conflicting results regarding the effect of shoulder injury on torque steadiness and torque matching accuracy. There are no studies that have focused on shoulder torque steadiness in the healthy populations, or how shoulder torque control may change in the presence of other variables relevant to injury risk, such as dual tasking, fatigue, and commonly used injury prevention strategies such as taping. In particular, dual tasking and fatigue have been highlighted in a recent consensus statement on shoulder injury prevention (Schwank et al., 2022) as factors that need further research and clinical consideration.

With respect to dual tasking, more is being understood about the link between neurocognitive function (such as working and visual memory) and injury risk. Dual tasking assesses one aspect of neurocognitive function, commonly by pairing motor tasks with cognitive tasks, to investigate the interference effect of one task on the performance of the other (MacPherson, 2018). While neurocognitive function has been frequently assessed in neurological populations, its relevance and implications in musculoskeletal rehabilitation has only attracted the interest of researchers in recent years (Walker et al., 2021). For example, a prospective study in a population of collegiate athletes found that those who suffered non-contact ACL injuries scored lower on neurocognitive scores compared to a matched control group (Swanik et al., 2007). That study, and other work in ACL populations, has led to recommendations

that clinicians integrate neurocognitive training, including dual tasking, into their shoulder injury prevention programmes (Schwank et al., 2022). However, to date, there have been no studies examining the effects of cognitive-motor dual tasking on torque control at the shoulder and there remain significant gaps in the knowledge base. For example, the choice of cognitive task and how it relates to real-world scenarios is an important consideration that has been previously highlighted (Walker et al., 2021), and should include higher-order cognitive challenges, rather than simple reaction time tasks. Similarly, examining dual task effect and the trade-off strategies between motor task and cognitive task performance is recommended to better understand changes in dual task performance (Plummer & Eskes, 2015). This knowledge may help clinicians and researchers better understand the dynamics between simultaneous cognitive and torque control tasks and how those may vary according to task complexity, with potential implications for injury prevention and rehabilitation. Accordingly, a study at the shoulder, exploring the effects of dual tasking on submaximal torque control, with a more complex choice reaction time task and examining dual task effects was conducted.

Fatigue is a known risk factor for injury at the shoulder (Kekelekis et al., 2020; Tripp et al., 2007) especially in overhead and throwing athletes, due to changes in muscle performance, co-ordination, and proprioception, all crucial for maintaining joint stability. Several studies have examined the effect of fatigue on measures of torque control at other joints as summarised in a recent review (Pethick & Tallent, 2022), but there is limited research on the shoulder. Only one study (Coskun et al., 2018) has investigated the effect of fatigue on torque control at the shoulder in a cohort of young, healthy males. While torque matching accuracy was unaffected by fatigue, the duration of fatigue was unclear and the authors did not measure variables of torque variability, such as steadiness. Furthermore, the researchers employed a maximum effort isokinetic fatiguing protocol, which may not always reflect muscle

fatigue induced during functionally relevant tasks (e.g. in a sporting context) where repeated submaximal efforts are common (Pethick & Tallent, 2022). Additionally, studies' use of visual feedback during torque control tasks is variable. Examining the torque control without feedback allows task performance decrements related to proprioceptive sensorimotor pathways that might otherwise be obscured with visual feedback present. Therefore, the present thesis includes a study investigating the effects of fatigue on submaximal torque control at the shoulder, both with and without visual feedback.

Taping is frequently used in the management and prevention of joint injuries, across all levels of sports participation. Rigid and elastic taping are both commonly used, with posited benefits being linked to limiting excessive movement, reducing tissue stresses, and improving sensorimotor control (Morrissey, 2000). When exploring its effects on sensorimotor control, taping studies have typically used joint position sense (JPS). There is a limited body of research examining the effect of taping on torque matching accuracy demonstrating the potential for taping to enhance torque matching accuracy, but, importantly, none have been completed on the shoulder (Ghai et al., 2023). Furthermore, no studies have investigated the effect of taping on torque steadiness or torque matching accuracy during more complex motor tasks that may be more representative of functional movement, such as torque tracking. Studying the effect of taping on shoulder torque steadiness and accuracy during torque matching and torque tracking tasks could provide insights into its potential benefits, with implications for motor performance and injury prevention. Thus, we investigated the effect of taping on shoulder torque control in a cohort of healthy active individuals.

1.2 Statement of the Problem

Arguments for the importance of adequate sensorimotor control of the shoulder in preventing injury and maximising performance are often observed in the literature.

Despite this communication, there are limited studies examining torque control at the shoulder, and most have used torque matching tasks at a single target level, in the presence of visual feedback. Furthermore, few have examined how torque control is affected by factors such as dual tasking, fatigue, and shoulder taping.

Thus, the aims of this research were to explore, in a cohort of healthy young adults, submaximal torque control at the shoulder and how it may be affected under different conditions relevant to injury risk.

To address these aims the following studies were conducted:

An investigation into the effects of dual tasking on isometric torque matching accuracy and torque steadiness of the shoulder internal and external rotators in a cohort of healthy young adults (described in Chapter 3). We hypothesised that, under dual task conditions with a visual-cognitive Stroop task: 1) shoulder internal and external rotation torque matching steadiness would decrease (reflected by increased SD), and torque matching accuracy would decrease (reflected by increased RMS); 2) torque tracking accuracy would decrease (increased RMS); and 3) Stroop task performance would decrease with reduced response accuracy and increased reaction time compared with single task conditions.

An investigation into the effects of local muscle fatigue on isometric torque matching and torque steadiness of the shoulder internal rotators in a cohort of healthy young adults (described in Chapter 4). We hypothesised that after the fatiguing protocol, torque accuracy and steadiness would decrease (increased RMS and SD respectively) under both visual feedback conditions. These decreases were expected to be significantly greater in the absence of visual feedback, where participants rely predominantly on proprioceptive sense of force.

An investigation into the effects of shoulder taping on isometric torque matching accuracy and torque steadiness of the shoulder internal and external rotators in a

cohort of healthy young adults (described in Chapter 5). We hypothesised that: 1) during a static torque matching task, taping would result in both improved torque steadiness (decreased SD) and torque matching accuracy (decreased RMS) in the absence of visual feedback; whereas no change was expected with visual feedback; and 2) taping would improve torque matching accuracy during a torque tracking task to a greater extent than torque matching without visual feedback.

1.3 Significance of this Doctoral Research

Despite frequent assertions about the importance of sensorimotor control for shoulder function, torque control research has predominantly focused on lower limb joints due to their established relationship with mobility and functional independence in aging populations. This research addresses a significant gap by investigating submaximal torque control at the shoulder, a joint with fundamentally different biomechanical demands that is frequently injured and relies on dynamic muscular control for stability. Understanding how torque steadiness and matching accuracy respond to experimental conditions with real-world relevance, such as dual tasking, fatigue, and taping, provides a foundation that has been largely absent in the shoulder literature. This thesis provides preliminary reference data for future research. This research offers several specific contributions to understanding shoulder sensorimotor control. First, it tests whether findings from lower limb and hand research, particularly regarding the sensitivity of torque steadiness and matching accuracy to attentional and physiological demands, translate to the unique neuromuscular context of the shoulder. Second, by examining three distinct experimental conditions (attentional demand, muscular fatigue, sensory augmentation via taping), the findings may reveal how cognitive, neuromuscular, and somatosensory factors differentially influence motor output and sensory feedback. Third, it establishes whether torque steadiness and matching accuracy represent dissociable constructs at the shoulder, which would indicate if motor output and

proprioceptive systems operate with some degree of independence at this joint, meaning that deficits in one need not predict deficits in the other. This has both methodological and clinical relevance; researchers assessing shoulder sensorimotor control may need to measure both constructs separately rather than treating either as a proxy for overall function, and may inform whether clinicians need to target motor output and sensory feedback through distinct rehabilitation strategies rather than assuming that improving one will transfer to the other. The selected laboratory-based experimental conditions were chosen for their practical and clinical relevance: dual-task demands mirror real-world situations where cognitive processing occurs alongside motor control; fatigue represents the repetitive loading characteristic of overhead work and physical exercise; and taping is a widely used clinical intervention whose effects on submaximal torque control remain poorly understood. While this research is conducted in healthy participants using controlled laboratory tasks, it establishes methodological approaches and provides preliminary insights into the differential effects of the experimental conditions that may guide future research in clinical populations. Characterising shoulder torque control under these conditions establishes methods for future research and offers a meaningful reference point against which the effects of injury, pain, or dysfunction can be more clearly understood.

1.4 Thesis Presentation

This thesis begins with a narrative review of the current literature on torque control, discussing its potential clinical importance, methods of assessment, and current understanding of the effects of dual-tasking, fatigue and taping on submaximal torque control. Subsequently, three experimental chapters are presented that explore shoulder submaximal torque control under dual-task conditions, following shoulder muscle fatigue, and investigating the effect of shoulder taping. Finally, an

overall discussion and conclusions chapter presents the implications for clinical practice and recommendations for future research.

Chapter 2: Literature Review

2.1 Introduction

The purpose of this chapter is to inform the reader of the relevance of torque control on shoulder function and how it may change under different conditions. The initial sections of this chapter will give an overview of relevant shoulder anatomy and sensorimotor control in human movement and function. Then a more in-depth review of the neurophysiological components of the sensorimotor system and related neuroanatomy of the shoulder is presented. The remainder of the chapter explores how torque control is assessed and review studies related to dual tasking, fatigue, and taping and what is currently known about their effects on torque control, including at the shoulder.

2.2 Literature Search

An initial review of the literature was conducted using numerous sources including textbooks, journal articles, reviews, conference material and grey literature through internet searches. Using the resultant information, the keyword list shown in Table 1 was used, including truncations, and in different conjunctions with various Boolean operators.

These keywords and phrases were used in an initial search of the following databases: MEDLINE, CINAHL, Embase, OVID, SPORTDiscus, and Scopus. Where necessary, the initial search was refined by modifying the keyword list and MeSH terms. The search was further supplemented with a manual search through bibliographies of identified key papers. Only full-text, peer-reviewed papers in the English language of studies with human subjects were included. The search of the literature was concluded by June 2023.

2.2.1 Search Terms

Table 1. Literature search terms

Main Term	Synonyms
Sensorimotor control	Neuromuscular control, motor control
Proprioception	Proprioceptive
Sense of force	Force sense, force appreciation, sense of effort
Force	Torque
Control	Modulation, scaling
Steadiness	Smoothness, stability
Matching	Tracking, accuracy
Shoulder	Upper limb, glenohumeral
Injury	Trauma, pathology, impairment, disability
Dual task	Multitask, divided attention
Taping	Strapping, support, brace
Fatigue	

2.3 The Mobile Glenohumeral Joint

The shoulder complex enables extensive upper limb function through the glenohumeral (GHJ), acromioclavicular, sternoclavicular joints, and scapulothoracic articulation. With a far greater ROM availability than at other peripheral joints (Horbaly et al., 2023), co-ordinated scapular motion positions the glenoid to take advantage of this ROM, supporting human versatility in tasks such as tool use, sporting activities, and throwing actions (Kuhn, 2016).

The GHJ, with its shallow glenoid fossa and large humeral head, provides exceptional mobility but limited congruence, with only ~30% of the humeral head in contact at any time (Halder et al., 2000). While the labrum and capsuloligamentous complex contribute to the passive stability of the GHJ (Bain et al., 2013; Howell & Galinat, 1989; Park, 2015), mechanical stability is inherently low (Lugo et al., 2008), placing greater reliance on dynamic stability provided via muscle action.

Bain et al.'s (2019) "crane model" highlights the interplay of passive and active stabilisers within the kinetic chain. The capsuloligamentous structures, aside from providing mechanical restraint to end range movements, provide sensory feedback while rotator cuff forces centre the humeral head, counterbalancing larger muscle forces, and generating a concavity–compression effect to enhance joint stability (Favre et al., 2005; Labriola et al., 2004, 2005; S.-B. Lee et al., 2000; Lippitt et al., 1993).

Ultimately, effective GHJ dynamic stability depends on neuromuscular control to maintain functional joint stability (Riemann & Lephart, 2002a, 2002b), with this control dependent on the sensorimotor system.

2.4 The Sensorimotor System

The term 'sensorimotor system' is used to describe "*the sensory, motor and central integration and processing components involved in maintaining joint homeostasis (functional joint stability)*" (Riemann & Lephart, 2002a). Neuromuscular control, a subset of sensorimotor control, refers to the interaction of the nervous and muscular systems to prepare for and regulate movement (Riemann & Lephart, 2002a, 2002b; G. N. Williams et al., 2001). Given this integration, the broader term *sensorimotor control* is adopted here in relation to torque control at the shoulder.

Seminal work at the turn of the millennium (Lephart et al., 2000; Riemann & Lephart, 2002a, 2002b) established a framework for understanding how sensory and motor integration supports peripheral joint stability during functional tasks. During arm movement, multimodal afferent input (visual, auditory, somatosensory) is compared with centrally generated predictions (e.g., corollary discharge, efference copy), with discrepancies eliciting corrective motor responses (Wasaka & Kakigi, 2019). While visual and vestibular inputs are essential to voluntary movement, this review focuses on proprioceptive contributions to sensorimotor control.

Proprioception—the ability to sense limb position, movement, and forces—has evolved conceptually from Bell’s “muscular sense” (Bell, 1826) and Sherrington’s work on proprioceptive neurons (Sherrington, 1906) to modern definitions incorporating joint position, kinaesthesia, force, effort, and velocity (Ager et al., 2020; Proske & Gandevia, 2012). The kinaesthetic senses are those concerned with limb position and movement. There is a large body of work on the role of kinaesthetic proprioceptive senses (Proske & Gandevia, 2012). This thesis investigates shoulder torque control, and therefore proprioception as it relates to torque control (sense of force and effort) are discussed with kinaesthetic measure only discussed where contextually relevant.

The senses of force and effort arise from voluntary contraction, with sense of effort largely centrally derived from efference copy, and sense of force originating from afferent input from Golgi tendon organs and muscle spindles (Luu et al., 2011; Proske & Allen, 2019). These mechanisms are directly relevant to torque matching tasks, where both senses may be recruited (L. A. Jones & Hunter, 1982).

2.5 Sensory Innervation of the Glenohumeral Joint

Mechanoreceptors are also present in the superior, middle and inferior glenohumeral (SGHL, MGHL, IGHL), and coracohumeral (CHL) ligaments (Guanche et al., 1999; Vangsness et al., 1995). The CHL, histologically similar to capsular tissue, shows a particularly high receptor density, suggesting a role in fine-tuning rotator cuff activity (Bain et al., 2019; Gohlke et al., 1998; Yang et al., 2009).

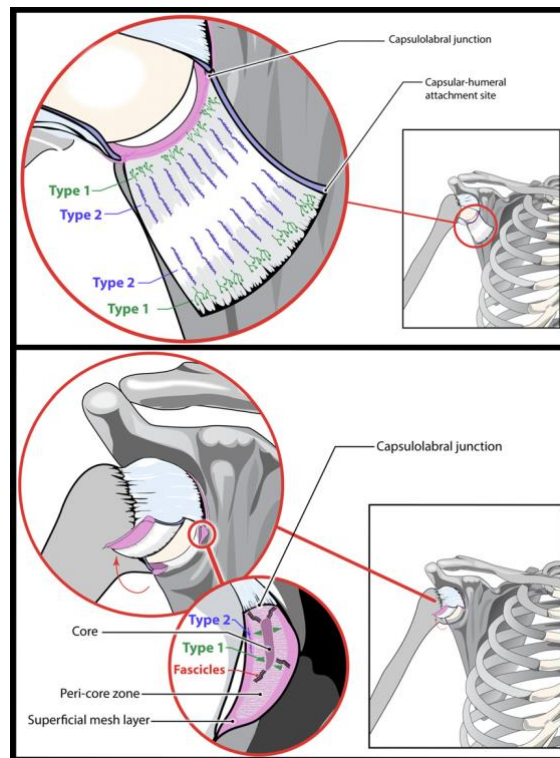


Figure 1. The distribution of Type I and II mechanoreceptors in the glenohumeral capsule [*reproduced from Witherspoon et al. (2014) with permission*]

Musculotendinous receptors further contribute to proprioceptive afferent input. While human evidence is lacking, animal studies confirm muscle spindles and Golgi tendon organs in the rotator cuff (Backenköhler et al., 1997; Yamashita et al., 1999). Muscle spindles are sensitive to muscle length change and velocity of movement (Proske, 2006), whereas GTOs detect muscle-tendon forces (Jami, 1992). Given the cuff's anatomical continuity with the capsule, its activity may also indirectly stimulate capsuloligamentous mechanoreceptors (Nyland et al., 1998).

Afferent signals from these peripheral mechanoreceptors are transmitted to higher centres via the spinal column ascending pathways (Figure 2). Conscious proprioceptive information (i.e. that provide us with a perception of limb position/movement) is conveyed through the dorsal column–medial lemniscus system to the somatosensory cortex, while unconscious signals (providing real-time information for co-ordination, balance etc.) are transmitted via the spinocerebellar

and cuneocerebellar tracts to the cerebellum (Kandel, 2013; Leo, 2022; Røijezon et al., 2015).

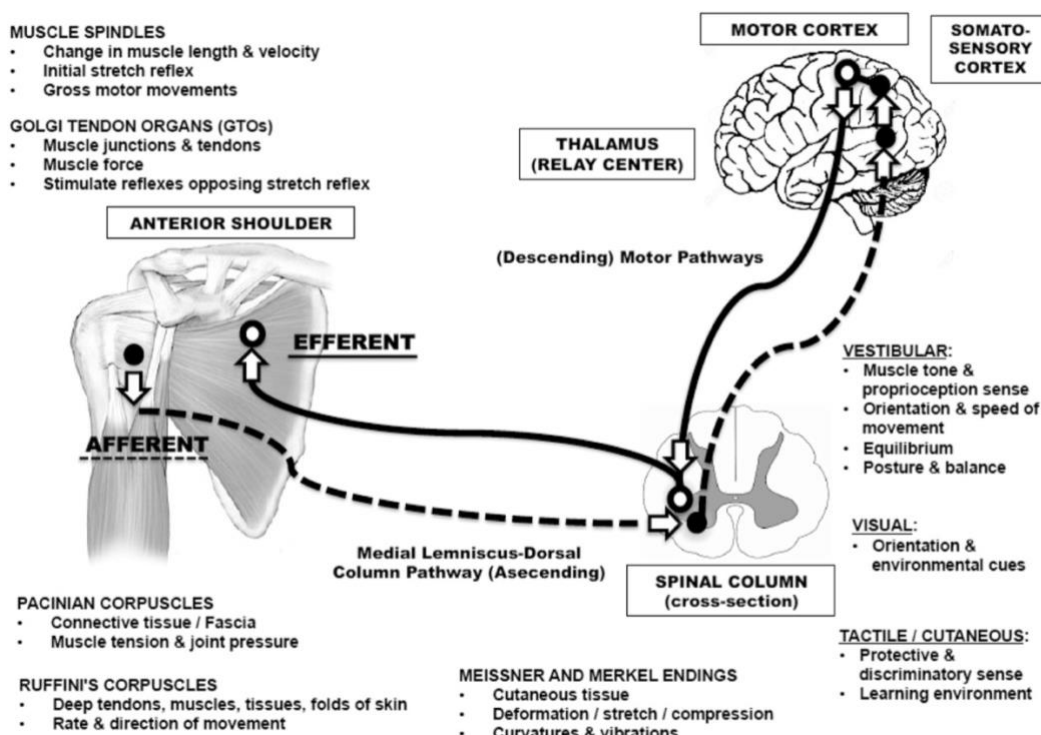


Figure 2. Shoulder proprioceptive pathways [reproduced from Ager et al. (2017) with permission]

2.6 Sensorimotor Integration

Sensorimotor integration combines afferent input with predicted sensory feedback from the efference copy to optimise body position, movement, and loading (Wasaka & Kakigi, 2019). These comparisons support moment-to-moment corrections and long-term motor learning, underpinned by evolving internal models of feedforward and feedback control (Franklin & Wolpert, 2011; Moreno-López et al., 2016; Wolpert & Miall, 1996). Feedback provides corrective responses, while feedforward enables anticipatory control (Honarvar et al., 2021). The discrepancy between the predicted and actual feedback allows for the system to adapt, minimizing movement variability and optimising control (Bays & Wolpert, 2007; Wolpert et al., 1995) (see Figure 3).

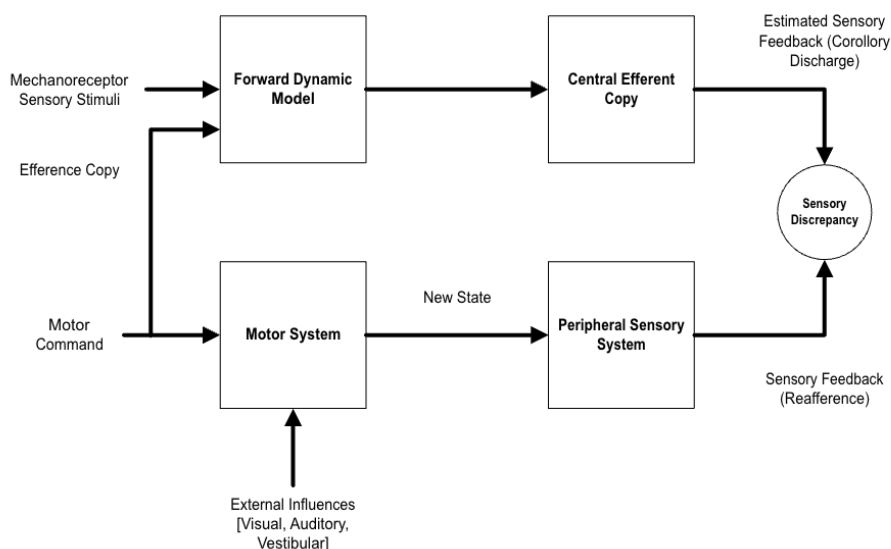


Figure 3. Centrally mediated sensorimotor integration [*adapted from work by Bays & Wolpert (2007)*]

At the spinal level, mono- and polysynaptic stretch reflexes have been observed in the rotator cuff muscles, with shorter latencies and greater amplitudes than larger shoulder muscles (Day et al., 2012; Nicolozakes et al., 2022). Reflex latencies have been observed to vary with contraction level, being faster under increasing isometric MVC (Myers et al., 2003). Importantly, reflex responses may also originate from capsular and ligamentous afferents. Electrical stimulation of the GHJ capsule has been demonstrated to elicit inhibitory effects on the rotator cuff, most notably the subscapularis, infraspinatus and supraspinatus (Voigt et al., 1998). Similarly, stimulation of the coracoacromial ligament led to general inhibition of shoulder muscles including the supra- and infraspinatus, deltoid, serratus anterior and upper trapezius (Diederichsen et al., 2004). Interestingly, these inhibitory effects from electrical stimulation are in contrast to facilitatory effects demonstrated from other studies investigating stretch-induced reflexes through GHJ perturbation (Augé & Morrison, 2000; Day et al., 2012; Nicolozakes et al., 2022). An explanation for these divergent findings could be the difference in afferent mechanoreceptor stimulation. Translational perturbations likely excite a diverse array of proprioceptors within the muscles, ligaments, and capsule surrounding the shoulder, whereas electrical stimulation studies targeted sensory afferents specific to the stimulated tissue. This

could have led to differences in sensory pathways being activated, resulting in different motor responses. Ecologically, perturbation studies are more representative of GHJ translations that have the potential to be injurious or that are encountered in real-world scenarios.

These findings highlight the influence of capsular, ligamentous, and musculotendinous mechanoreceptors on reflexive shoulder muscle activity. While the exact pathways remain unresolved, afferent feedback from structures such as the rotator cuff GTOs and CAL mechanoreceptors appears critical for coordinated motor control (Bachasson et al., 2015; S. R. Ward et al., 2006). Sensory afferent input at the spinal cord can also be moderated by the CNS via the corticospinal tract (CST) and its connections with excitatory and inhibitory spinal interneurons (Moreno-López et al., 2016). This allows for cortical control of sensory afferent input indicative of the ability of the cortex to have some selective control over ascending sensory information for additional movement control. The functional significance of this cortical control over sensory feedback interneurons is to allow the sensorimotor cortex to selectively filter and shape the sensory information that is relevant for the execution of voluntary movements, thereby increasing the signal-to-noise ratio in the motor output (Moreno-López et al., 2016). Beyond simple gating of afferent input, this capacity for top-down modulation suggests that the cortex can dynamically recalibrate reflex pathway sensitivity in a task- and context-dependent manner, affording a more flexible and precise degree of movement control than spinal networks alone could provide.

2.7 Motor Output

Following sensorimotor integration and processing, descending tracts deliver voluntary motor commands from the motor cortex that activate alpha motor neurons, culminating in motor unit recruitment and muscle force production (Enoka & Pearson, 2013; Heckman & Enoka, 2012). Motor output reflects a balance of

excitatory and inhibitory inputs from spinal and supraspinal sources, including mechanoreceptor feedback (Heckman & Enoka, 2012). Force generation depends on motor unit recruitment, rate coding, fibre characteristics, and muscle architecture (Duchateau & Enoka, 2011; Enoka & Duchateau, 2017).

The rotator cuff originates from the scapula and inserts onto the humeral head, positioning it to provide dynamic GHJ stability (Hess, 2000). By compressing the humeral head into the glenoid and resisting shear forces, the cuff maintains the joint's axis of rotation against destabilising vectors from larger muscles such as the deltoid, pectoralis major, and latissimus dorsi (Akhtar et al., 2021; S.-B. Lee et al., 2000; Lippitt et al., 1993).

The cuff demonstrates feedforward stabilising behaviour, activating prior to larger muscles during voluntary perturbations (David et al., 2000) and pre-activating in response to anticipated external loads (Day et al., 2012). Additionally, Day and colleagues reported that activation is direction-specific, with subscapularis and infraspinatus showing moderate activity when resisting opposing rotations.

Contraction of the cuff also increases GHJ stiffness, mitigating excessive humeral head displacement (Nicolozakes et al., 2022). This effect was shown to be greatest in the neutral position, with capsuloligamentous structures such as the IGHL providing greater resistance in the apprehension position.

2.8 Summary

The glenohumeral joint achieves exceptional mobility through its shallow glenoid fossa and large humeral head. However, this anatomical design provides limited inherent mechanical stability, placing greater reliance on dynamic stabilisation that is fundamentally dependent on sensorimotor control. Mechanoreceptors distributed throughout the GHJ capsule, labrum, ligaments, and rotator cuff provide multimodal proprioceptive information regarding joint position, movement, and the senses of

force and effort that ascend via spinal pathways to higher centres for sensorimotor integration. This afferent information is compared against predicted sensory feedback from the efference copy, enabling both feedforward anticipatory control and feedback-based corrective responses that minimise movement variability and optimise motor performance. The resulting motor output, particularly from the rotator cuff muscles, demonstrates direction-specific, anticipatory activation patterns that provide stability by compressing the humeral head into the glenoid and counteracting destabilising forces from the larger shoulder muscles. Thus, torque control at the shoulder is mediated through a sophisticated integration of proprioceptive feedback, spinal reflexes modulated by cortical input, and motor output adjustments. These mechanisms underpin the capacity for shoulder functional joint stability and precise control during physical activity.

2.9 Submaximal Torque Control

2.9.1 Introduction

Muscle torque control is concerned with the steadiness and/or accuracy of voluntary muscle force production measured via electrical signals obtained from load cells positioned to respond to changes in torque being generated across a joint (Clark & Pethick, 2022; Hortobágyi et al., 2004; Rice et al., 2015). Measurement of submaximal torque control enables researchers to speculate on mechanisms concerning the function of the sensorimotor system in different contexts, such as learning a new skill, improving physical performance, and recovering from an injury or medical condition (Enoka & Farina, 2021).

A primary approach for quantifying torque control involves analysing sustained isometric muscular torque production. Typically, an isokinetic dynamometer is used to record a person's torque production at a pre-determined level, for a given epoch (Riemann et al., 2002). The torque-time signal can then be analysed, and different metrics associated with the production and regulation of torque can be produced,

allowing researchers to gain insights into different aspects of the systems involved (Enoka & Duchateau, 2017; Ostry & Feldman, 2003; Slifkin et al., 2000; Vieluf et al., 2017). These metrics and their relationship to sensorimotor mechanisms are discussed below in Section 2.9.3 and 2.9.4.

2.9.2 Torque Control Tasks

Matching a single static target torque is a commonly used approach for examining torque control. This can be assessed within contralateral matching tasks where an individual attempts to produce torque in one limb to match a given produced torque in a contralateral reference limb (e.g. Brooks et al., 2013; Carson et al., 2002; Jones, 1986, 1989; Proske et al., 2004). Conversely, torque matching tasks can be performed in the ipsilateral limb (e.g. Rice et al., 2015; Skurvydas et al., 2011; Vieluf et al., 2017). In this case the individual attempts to reproduce a previously generated torque. Whilst both ipsilateral and contralateral matching tasks provide some challenge to torque control; there are task dependent differences. For example, contralateral tasks are thought to involve the sense of effort derived from centrally generated efferent copies of motor commands (Jones, 1995; McCloskey et al., 1974; Monjo & Forestier, 2018; Proske & Allen, 2019) and involve interhemispheric transfer of information for task performance (Goble & Brown, 2008). Ipsilateral tasks by contrast, are thought to rely more on working memory and a sense of muscular tension mediated by peripheral afferent input from muscle spindles and GTOs (Jami, 1992; Proske & Allen, 2019). Whilst both methods offer insight into sensorimotor mechanisms, ipsilateral tasks have greater functional relevance, as we don't tend to move/function by comparing efforts between limbs, rather, we use our limbs independently with unconscious control but driven by external goal-oriented task execution. Contralateral tasks may be better suited to investigating neurological populations where injury to one hemisphere may impact performance across limbs, whereas ipsilateral tasks are more commonly used in non-neurological populations.

An inherent issue with a static torque target matching task is the ecological validity and relevance to real-world scenarios (Ward et al., 2019). When generating torque across a joint, the motor system rarely, if ever, produces a steady force of a single agonist. In many functional activities, torque production needs to be modulated and coordinated between agonists and antagonists to facilitate appropriate movement execution. However, employing more complex torque control tasks involving multi limb/joint movement make studying torque output constructs a challenge due to potential confounding external/environmental influences on resultant torque control fluctuations (Furness et al., 1977).

A compromise may be to use a variable target torque trace that requires a participant to modify their torque as they track the continually changing target trace. Tracking tasks include compensatory, pursuit and preview tasks (R. Jones, 1999). Pursuit tasks display the target and participant output simultaneously. Compensatory tasks display only the difference between target and produced torque. The preview task is similar to the pursuit task, but the target torque is previewed meaning participants have the opportunity to plan their action. Compensatory tasks have the least similarity with everyday tasks, whereas preview tasks share the greatest parallel with everyday function (R. Jones, 1999).

Torque tracking tasks are of interest because they assess the CNS processing systems and synaptic inputs involved in grading muscular torque production. They also allow examination of how real-time prediction and feedback of task performance influence motor control (C.-Y. Huang et al., 2014; R. Jones, 1999). They have been previously examined in the literature to investigate the ability to accurately modulate force, rate coding of motor unit recruitment, force gradation strategy, and visual feedback influences on torque control (Chen et al., 2017; Huang et al., 2014; Knight & Kamen, 2007; Patten & Kamen, 2000). These studies typically used sinusoidal presentations of variable target torques and frequencies, and the performance of

these visual motor tasks represent both the feedforward and feedback mechanisms of the sensorimotor system (C.-Y. Huang et al., 2014).

In studies of non-neurological populations such as healthy participants and those with musculoskeletal injuries, the use of torque tracking tasks has been limited to the lower limb. Differences in torque tracking accuracy have been observed between younger and older adults (Patten & Kamen, 2000) with older adults demonstrating a 39% greater RMS error for ankle dorsiflexion torque tracking than younger counterparts. At the knee, previous studies in ACL populations have demonstrated greater torque matching error in those with ACL injury (S. H. Ward et al., 2019) and in ACL-reconstructed individuals compared with controls (Perraton et al., 2017; Rice et al., 2020).

2.9.3 Torque steadiness

Several measures of torque control have been reported. Fluctuations in muscle torque signals are measured via magnitude variables of torque steadiness including the standard deviation (SD) and coefficient of variation (CV) over a given epoch (Figure 4) (Enoka et al., 2003; Galganski et al., 1993; Santos et al., 2016; Slifkin & Newell, 1999). These measures represent the deviation from a fixed-point in a time series (Pethick, Clark, et al., 2022; Slifkin & Newell, 1999). Using SD is considered more representative of steadiness, as it is an absolute measure of torque variability whereas CV is a relative measure normalised to the mean torque and is preferable when comparing different groups, to account for differences in absolute target torque values (Camargo et al., 2009; Pethick et al., 2015).

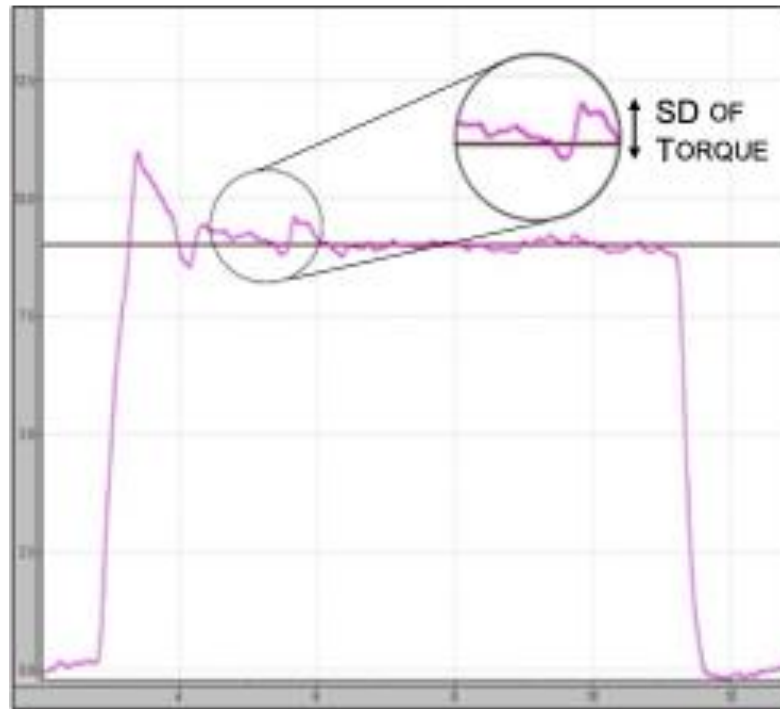


Figure 4. Visual representation of torque steadiness (SD)

More recently, temporal constructs of torque complexity (e.g. SampEn) have gained popularity. However, the relevance of such measures to studying torque control and correlations with functional task performance are limited in comparison to more commonly used measures of torque control (Pethick et al., 2021). As discussed in Section 2.7, motor units receive inputs from a wide variety of descending, spinal and sensory synaptic connections. Inputs across functional groups of motor neurons are known as common input, whereas inputs to single motor neurons are classified as independent (Hug et al., 2023). These synaptic inputs are transformed into output spike trains and subsequently motor unit recruitment. (Enoka & Farina, 2021; Farina et al., 2014; Farina & Negro, 2015).

Torque steadiness may be most unsteady at very low (<10%) and high (>50%) isometric contraction intensities (Enoka et al., 2003; Enoka & Farina, 2021), and typically the absolute amplitude of torque fluctuations increases with an increase in mean torque (Enoka & Farina, 2021). In general, it is thought that torque production >10% MVC removes influences on torque steadiness associated with synaptic noise

(background noise from fluctuating motor neuron membrane potentials) (Dideriksen et al., 2012).

Construct validity for magnitude measures of torque fluctuations, such as the standard deviation (SD) of torque, is supported by computational and theoretical work linking these measures directly to the common synaptic input received by motor neurons. Dideriksen et al. (2012) demonstrated through computational modelling that the magnitude of force fluctuations during isometric contractions is predominantly determined by the common synaptic input shared across motor neurons in a pool, rather than by variability intrinsic to individual motor neurons or peripheral mechanical factors. Their simulations showed that as the amplitude of common input variability increases, so too does the variability in the resulting force output, establishing a direct and quantifiable relationship between the neural drive and magnitude-based measures such as SD. This is a particularly important finding because it suggests that SD of torque is not merely a performance outcome but reflects a genuine neural signal, specifically the degree of fluctuation in the shared descending drive to the motor neuron pool.

Farina & Negro (2015) extended this theoretical framework by characterising motor neuron pools as low-pass filters on their synaptic input, cancelling out the independent inputs to motor neurons and transmitting the common input components to generate the effective neural drive to the muscle. This neural drive closely matches the common synaptic input to the motor neurons, which is the main determinant of force production. Together, these studies establish that SD of torque is a valid construct measure of common synaptic input, meaning that any experimental condition or population characteristic that modifies the common neural drive, such as fatigue, aging, or neuromuscular pathology, should produce corresponding and interpretable changes in SD.

Torque steadiness during submaximal isometric contractions reflects the fidelity with which the nervous system transmits a stable excitatory drive to the spinal motor neuron pool. The primary determinant of torque fluctuations is not the independent inter-spike interval variability of individual motor units but rather the slow, correlated oscillations in discharge rate shared across motor neurons, driven by common synaptic input from descending cortical and subcortical pathways and from sensory afferents (Farina et al., 2014; Negro et al., 2009). Muscle spindle Ia afferents are a critical component of this common input. They impose a tonic, length-sensitive bias on motor neuron excitability that stabilises discharge timing, and their removal amplifies low-frequency common drive oscillations and worsens torque steadiness in proportion to the degree of afferent loss (Dideriksen et al., 2012). Tendon vibration manipulates this same channel; when it saturates primary spindle endings or superimposes a tonic vibration reflex on voluntary drive, torque fluctuations increase (Saito et al., 2016; Shinohara et al., 2009). The variance in common synaptic input predicts force CV with correlations of $R^2 \approx 0.59-0.80$, substantially exceeding predictions based on individual discharge variability alone (Castronovo et al., 2018; Feeney et al., 2018), and it is this common input variance that increases with ageing (Castronovo et al., 2018; Tracy et al., 2005), disease (Pethick, Clark, et al., 2022), and fatigue (Pethick & Tallent, 2022). Torque steadiness is therefore best understood not as a property of individual motor units but as an emergent output of the entire sensorimotor loop. The stability of voluntary torque reflects how cleanly the nervous system can suppress low-frequency noise in the integrated synaptic current driving the motor neuron pool, a process that depends on the coherence and regularity of all converging inputs; descending, spinal, and afferent.

Both SD and CV of torque show expected deficits across groups such as older adults (Pethick & Tallent, 2022), and those with joint injury (Pethick, Clark, et al., 2022). In addition, submaximal torque matching steadiness has been shown to

correlate with performance on functional tasks related to sensorimotor function and that these associations are often stronger than other frequently used metrics such as muscle strength (Enoka & Farina, 2021).

For example, Almuklass et al. (2016) examined peg board dexterity in young adults finding that much of the variance in performance was due to a model comprised of time to match a target torque and torque steadiness ($R^2=.70$; wrist extensor CV at 10% MVC $r=-.48$), whereas multiple strength measurements were not significantly correlated with performance (hand grip $r=.11$; wrist extension; $r=.21$; pinch grip $r=.03$; finger abduction $r=.10$). Similarly, a study (Davis et al., 2020) investigating postural sway in an adult population demonstrated that hip abductor torque steadiness was the most consistent explanatory variable for postural sway across a range of test conditions (*Partial R*=.33, .46, .31, and .69) whereas plantar flexor MVC was only significant for one of the test conditions (*Partial R*=-.37). In a cohort of healthy adults, isometric knee extensor steadiness (CV) at 40% MVC was more strongly correlated with a dynamic Y-balance reach performance (anterior reach $r=-.44$, $p=.02$; posteromedial reach $r=-.51$, $p=.006$) than MVC (posteromedial reach $r=.39$, $p=.043$) (Mear et al., 2022). Hirono et al. (2020) demonstrated that ankle plantar flexor steadiness was significantly correlated with balance (centre of pressure) on stable (CV at 5%MVC $r=.51$, $p=.02$) and unstable platforms (CV at 20%MVC $r=.46$, $p=.07$) whereas MVC was not (unstable $r=0.05$, $p=0.78$; stable $r=.30$, $p=.09$). Together these findings suggest the correlation of torque steadiness with functional measures reflects a consistent neuromuscular mechanism rather than a task specific, or single-muscle phenomenon.

2.9.4 Torque matching accuracy

Torque matching accuracy relates to how accurately a torque is produced relative to a given target torque. In the absence of visual feedback, the prevailing mechanism on the ability to accurately match torque is thought to relate to the sense of force

(see Proske & Allen, 2019, for review). Typically, when investigators are exploring sense of force, they measure torque matching accuracy. Variables for assessing accuracy include absolute error (AE), constant error (CE) and variable error (VE) (Röijezon et al., 2015). These variables relate to different aspects of accuracy, with CE the average deviation between target and actual torque, AE is the overall deviation (irrespective of direction of error), and VE is calculated using the standard deviation of either the absolute or constant error (Schmidt et al., 2018). Constant error reflects *where* someone is aiming relative to a goal, VE informs of how *reproducibly* they perform, and AE gives a combined summary of both. Another commonly used variable in the measurement of torque matching accuracy is RMS error (Figure 5) (Kiyama et al., 2014; Magni et al., 2021; Perraton et al., 2017; Rice et al., 2015; Telianidis et al., 2014; Trouset et al., 2018; Ward et al., 2019). As the name implies, root mean square error is the square root of the mean of the square of the differences between the target and output torque. It is expressed in the same units as the output variable (Nm). To evaluate motor performance across the full duration of a contraction, RMS error offers a more robust assessment of torque control than CE or AE. Unlike CE, which allows directional biases to cancel out, or mean AE, which treats all deviations linearly, RMS error disproportionately weights larger excursions from the target (Crenna et al., 2021; Duarte et al., 2019). This sensitivity is critical for identifying intermittent mid-contraction instabilities and low-frequency drift that may otherwise be obscured. Furthermore, RMS error may be preferable to VE because it serves as a global indicator of total error (Schmidt et al., 2018). While VE measures only the consistency of the signal around the participant's own mean, RMS error incorporates both variability and systematic bias (accuracy) relative to the absolute target.



Figure 5. Visual representation of torque matching accuracy (RMS). The shaded area represents the difference between the participant's produced torque (magenta line) and the target torque (black line).

Combining accuracy and steadiness measures for torque matching tasks provide complementary information. Measuring torque steadiness allows for assessment of influences on the common synaptic input to motor neurons, and accuracy measures provide insight into primarily proprioceptive (sense of force) influences on torque output accuracy. Additionally, torque tracking tasks may be more sensitive to change than a static matching task due to additional temporal constraints and requires greater sensorimotor integration and adaptation to the time-varying target torque (Knol et al., 2019). In contrast, a static matching task allows for torque steadiness to be interrogated more freely.

2.10 Findings from Clinical Studies

Studies of submaximal torque control enable researchers to assess the function of the sensorimotor system in different contexts, including after musculoskeletal injury (Enoka & Farina, 2021). This knowledge has facilitated research into the potential clinical relevance of these findings by investigating relationships with function, injury, and the effects of age.

In older adults, age-related changes in the neuromuscular system results in reduced capacity for muscle force generation and torque control (Enoka et al., 2003; Hunter et al., 2016). These changes are most apparent with the magnitude and complexity of torque steadiness, and critically these changes are associated with functional measures relevant to ADLs such as balance, gait and manual dexterity (see Pethick, Taylor, et al. (2022) for a recent review of the literature).

Following peripheral joint injuries, sensorimotor deficits have been shown to persist even after surgery. For example, torque control deficits of the quadriceps have been demonstrated in those with knee OA (Hortobágyi et al., 2004), following ACL reconstruction (Perraton et al., 2017; Rice et al., 2020; Telianidis et al., 2014; S. H. Ward et al., 2019), and with shoulder instability (Sacco et al., 2014). These impairments could be due to the impact of injury at multiple levels of the sensorimotor system, including damage to capsuloligamentous structures and disruption of mechanoreceptors (Myers et al., 2006), central neuroplastic cortical changes (Livett et al., 2022), and changes in muscle activation patterns (Myers et al., 2004). These ongoing deficits are considered to increase the risk of re-injury and joint pathology (Fulton et al., 2014), and research has continually called for rehabilitation to address these deficits, particularly at the knee (van Melick et al., 2016) and shoulder (Cools et al., 2016).

In the presence of musculoskeletal injury and/or surgery, a meta-analysis (Pethick, Clark, et al., 2022) found an overall significant effect on torque steadiness (CV; SMD = 0.19 [95 % CI 0.06, 0.32]). The 14 included studies involved a total of 694 participants (n=358 with peripheral musculoskeletal injury and n=336 healthy controls). Of these studies, eight studies investigated torque control at the knee (six investigating ACL injury and two tibiofemoral osteoarthritis), five studies at the shoulder (four studies investigated shoulder impingement/SAPS and one SLAP lesions) and one study at the elbow (chronic elbow pain).

For the included shoulder studies, no overall significant effect was demonstrated for shoulder injuries on shoulder torque control. However, this may be due to the heterogeneity in testing procedures, and variables. Furthermore, it was highlighted that the majority of the studies at the shoulder included in the review were investigating subacromial impingement/SAPS. This pathology relates to structures in the subacromial space which do not contain any capsuloligamentous or articular structures. It is therefore possible that these relatively mechanoreceptor devoid structures provide limited proprioceptive input into the sensorimotor system and any injury to these structures may have limited impact on torque control. The studies at the shoulder are discussed in more detail in the following section.

2.11 Torque Control at the Shoulder

Numerous researchers have studied kinaesthetic and joint position sense measures of proprioception at the GHJ, especially in the presence of pathology, including shoulder instability (Hung & Darling, 2012; Lubiowski et al., 2019; Smith & Brunolli, 1989), impingement syndrome (Dilek et al., 2016; Machner et al., 2003; Sahin et al., 2017), rotator cuff pathology (Anderson & Wee, 2011; Gumina et al., 2019; Pairot de Fontenay et al., 2020), and experimentally induced pain (Sole et al., 2015). The kinaesthetic and position sense deficits observed in these, and similar studies have been detailed in previous systematic reviews (Ager et al., 2020; Fyhr et al., 2015). Prevailing theories of mechanisms of effect include altered proprioceptive afferent input from muscle and/or joint mechanoreceptors leading to changes in the efferent pathway.

In contrast, measures of torque control at the shoulder remain relatively under-examined, as highlighted by previous narrative reviews (Clark et al., 2015; Han et al., 2016) and a systematic review (Hillier et al., 2015) on proprioception. Given the unique architecture of the shoulder and its reliance on optimal sensorimotor control for healthy function and maintaining stability, the lack of studies investigating

shoulder torque control is somewhat surprising. The studies that have assessed torque control have largely investigated measures such as steadiness and accuracy in populations with shoulder injury or following neurological insult such as a stroke. The following section explores the research investigating shoulder torque control in non-neurological populations.

2.11.1 Study characteristics

The main characteristics of these studies are displayed in Table 2. All studies (n=9) used dependent variables related to torque steadiness, whereas only two studies investigated torque matching accuracy. Shoulder movements investigated included shoulder abduction (n=6) and shoulder internal and external rotation (n=4) in a variety of test positions. Whilst shoulder movements assessed were rationalised for the muscles of interest, no studies provided a rationale for test position. Most (n=6) examined the shoulder in 80-90° of elevation in the scapula plane, with three of these studies adding between 45° and 90° of external rotation. Presumably these positions were chosen to reflect some challenge to the rotator cuff muscles as the primary dynamic stabilisers of the GHJ. Higher angles of elevation combined with external rotation are particularly pertinent given that this represents the ranges involved in overhead sports and vocational tasks, where injuries are more common and associated with risk of shoulder injury (Asker et al., 2018; Wærsted et al., 2020).

All studies used an isometric torque matching task, and three studies also included isokinetic torque matching. No studies used a tracking task which could increase task complexity and provide a challenge more representative of typical alternating agonist/antagonist cyclic muscle activity commonly seen in sporting and vocational tasks (Garg et al., 2006; Illyés & Kiss, 2005; Sangwan et al., 2015; Sood et al., 2007). Target torques were varied across studies ranging from 20-60% of MVC which represents the wide range of muscle activity observed at the shoulder and

those reported in the stabilising role of the rotator cuff (Day et al., 2012; Huxel et al., 2008; Zhang et al., 2000).

The majority of studies (n=7) only examined torque control under a visual feedback condition. Torque matching without visual feedback is an example of an open-loop feedforward mechanism whereby an individual attempts to match a previously presented target torque based on internal representations and proprioceptive afferent input rather than visual error correction. Only examining torque control in the presence of visual feedback therefore limits the ability to assess the role of proprioceptive modulation of sensorimotor control. Additionally, the potency of visual feedback on task performance may have attenuated any potential change in torque control in the groups of interest.

Most studies (n=7) compared groups with shoulder pathology to matched healthy controls, and two studies used healthy individuals (one investigating experimentally induced pain, and the other comparing effect of shoulder elevation angle and load). Overall sample sizes ranged from 9 to 70 (median=30) dependent on study design and numbers of groups. Two studies used male only participants, one study looked exclusively at females, whilst two studies did not report on participant gender. The remaining studies (n=4) used groups with a mix of male and female participants. The heterogeneity of group genders makes direct comparison across studies difficult due to potential sex differences in motor unit behaviour (Lulic-Kuryllo & Inglis, 2022).

Table 2. Study characteristics for studies on shoulder torque control

Study incl. year	Study Design	Participants	Tested Limb	Shoulder Test Position	Task Parameters	Main Outcome Measures	Main Findings
Bandholm et al. (2006)	Cross-sectional	Subjects with SIS (n=9, 28.3±5.3yrs); Matched controls (n=9, 27.7±4.2yrs); Gender not reported	Dominant in both groups	Isometric: 90° abduction in scapula plane Isokinetic: 30-120° abduction in scapula plane	Isometric and isokinetic GHJ abduction; 20%, 27.5%, 35% MVC TF	SD, CV	Isometric: No sig difference between groups; both groups demonstrated increased SD/CV with increased TF; Isokinetic: Increased SD/CV at 35% TF in SIS concentrically; no other between group differences
Bandholm et al. (2008)	Cross-sectional	Healthy subjects (n=9; 22-37yrs); Gender not reported	Dominant	Isometric: 90° abduction in scapula plane Isokinetic: 30-120° abduction in scapula plane	Isometric and isokinetic GHJ abduction; 20, 27.5, 35% MVC TF	SD, CV	Following experimentally induced pain, significant increased SD but not CV for isometric; No difference for isokinetic
Camargo et al. (2009)	Cross-sectional	SIS group (n=27; 33.38±9.94yrs; 9F:18M); Matched controls (n=23; 32.26±9.04yrs; 8F:15M)	Injured limb (matched limb in control group)	80° elevation in the scapula plane	Isometric GHJ abduction; 35% MVC TF	SD, CV	No significant differences between groups
Overbeek et al. (2020)	Cross-sectional	SAPS group (n=40; 50±6.38yrs; 23F:17M) Control group (n=30; 51±5.71yrs; 17F:13M)	Injured limb (matched limb in control group)	Arm by side, GHJ in external rotation	Isometric Abduction and Adduction TMT at 60% MVC	SD, CV ApEN	SAPS group had significant decreased SD and CV cf. controls for abduction; SAPS groups had significantly lower ApEN cf. controls for abduction and adduction
Maenhout et al. (2012)	Cross-sectional	RCT group (n=36; 43.13±13.8yrs 22F:14M); Matched Controls (n=30; 41.45±13.1yrs; 15F:15M)	Dominant	45° elevation in scapula plane; 90° Elbow flexion	Isometric GHJ IR & ER; 50% MVC TF	RE, CE; SD, CV	RCT group overestimated torque cf. controls who underestimated; No significant difference between groups for accuracy or steadiness

Saccol et al. (2014)	Cross-sectional	Male athletes: ASI group (n=10, 22.6±3.4yrs); SLAP group (n=10, 26.9±4.7yrs); ASI matched controls (n=10, 22±3.4yrs); SLAP matched controls (n=10; 26.4±4.5yrs)	Injured limb (matched limb in control group)	Isometric: 90°abduction; 90° external Rotation; 90° elbow flexion Isokinetic: 90°abduction; 0-90° external Rotation; 90° elbow flexion	Isometric and Isokinetic GHJ IR & ER; 35%MVC TF	SD, CV	SLAP group impaired TS cf. Controls; Lower peak torque in ASI for IR and ER but not ER:IR
Trousset et al. (2018)	Cross-sectional	Healthy subjects (n=12; 6F:6M; 21.3±0.9yrs)	Dominant	50°, 70°, 90° elevation in scapula plane	Isometric abduction at 120%, 140% and 160% of baseline torque	CE, RMS	Decreased CE with increased TMT load; Decreased RMS error at 50° compared with 70° and 90°
Zanca et al. (2010)	Cross-sectional	SIS group (n=14, 36.57±5.23yrs); Healthy controls (n=15, 35.53±5.46yrs); All female	SIS group: Both limbs Controls: Matched	90° elevation in scapula plane; 45° and 75° of ER	Isometric GHJ IR and ER; 50% MVC TF	SD, CV	No significant difference between groups or between limbs in SIS group
Zanca et al. (2013)	Cross-sectional	OH athletes w SIS (n=21, 22.1±2.7 yrs); Asymptomatic athletes (n=25, 21±2.1yrs); Non-athletes (n=21, 22.2±2.4yrs); All male	Dominant	90°abduction; 90° external Rotation; 90° elbow flexion	Isometric GHJ IR and ER; 35% MVC TF	SD, CV	Higher SD for IR in asymptomatic athletes cf. non-athletes; No significant differences between groups for other variables

Note: SIS=shoulder impingement syndrome; SAPS = subacromial pain syndrome; RCT=rotator cuff tendinopathy; ASI=anterior shoulder instability; OH=overhead; GHJ=glenohumeral joint; TMT=torque matching task; MVC=maximum voluntary contraction; TT=target torque SD=standard deviation; CV=coefficient of variation; ApEn=approximate entropy; AE=absolute error; CE=constant error; RMSE=root mean square error cf. = compared

2.11.2 Study reporting quality

The reporting quality of the studies discussed in this section as assessed via the Appraisal Tool for Cross-Sectional Studies (AXIS) (Downes et al., 2016) are presented in Table 3. All studies used a cross-sectional study design with clear aims; however, the majority of the studies (n=8) did not provide a rationale for sample size. This raises concerns about statistical power and the risk of type II error. Furthermore, information concerning the sample frame and participant recruitment was missing in most studies (n=5), and three studies inadequately reported on study participant details in their results. This lack of information leads to uncertainty in whether the participants were truly representative of the target population and increases risk of bias.

Across all the studies, a lack of reporting on effect sizes, or sufficient data reporting for effect size calculations, prevents comparison across studies and makes it difficult to know whether statistically significant findings represent meaningful differences with respect to magnitude. Finally, only four studies appropriately addressed study limitations in their discussion. Not reporting study limitations makes it difficult to contextualise findings, making it difficult for readers to assess the generalisability of the findings themselves. These limitations should be borne in mind when interpreting the findings discussed in the following sections.

Table 3. Reporting of AXIS items for shoulder torque control studies

	AXIS Description	Bandholm et al. (2006)	Bandholm et al. (2008)	Camargo et al. (2009)	Maenhout et al. (2012)	Overbeek et al. (2020)	Saccol et al. (2014)	Trousset et al. (2018)	Zanca et al. (2010)	Zanca et al. (2013)	Overall n(%)
1	Were the aims/objectives of the study clear?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
2	Was the study design appropriate for the stated aim(s)?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
3	Was the sample size justified?				✓						1(11)
4	Was the target/reference population clearly defined? (Is it clear who the research was about?)	✓	✓	✓	✓	✓	✓		✓	✓	8(89)
5	Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation?				✓	✓	✓		✓		4(44)
6	Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation?			✓	✓	✓	✓		✓		5(55)
7	Were measures undertaken to address and categorise non-responders?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
8	Were the risk factor and outcome variables measured appropriate to the aims of the study?										

9	Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted or published previously?			✓	✓	✓	✓			✓	5(56)
10	Is it clear what was used to determined statistical significance and/or precision estimates? (e.g. p-values, confidence intervals)	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
11	Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
12	Were the basic data adequately described?			✓	✓	✓	✓			✓	6(67)
13	Does the response rate raise concerns about non-response bias?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
14	If appropriate, was information about non-responders described?	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
15	Were the results internally consistent?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
16	Were the results presented for all the analyses described in the methods?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
17	Were the authors' discussions and conclusions justified by the results?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)
18	Were the limitations of the study discussed?			✓		✓	✓			✓	4(44)

19	Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?	✓	✓	✓	✓	✓	✓		✓	✓	8(89)
20	Was ethical approval or consent of participants attained?	✓	✓	✓	✓	✓	✓	✓	✓	✓	9(100)

Note: ✓ denotes adequate reporting; blank cells denote either an absence of, or insufficient reporting

2.11.3 Summary of study findings

The relationship between shoulder pathology and torque control remains poorly understood, with the available evidence presenting divergent findings. Rather than supporting a clear impairment model, the literature reveals that pain, chronicity, activity level, and testing conditions each appear to independently influence torque steadiness in ways that are not yet fully understood.

A notable inconsistency emerges from within the same research group. Bandholm et al. (2006) found steadiness deficits in SAPS only during concentric contractions, yet when the same group induced experimental pain in healthy participants, deficits appeared under isometric conditions instead (Bandholm et al., 2008). The authors attributed this reversal to potential neuroplastic adaptations that accompany chronic pain, although this has never been directly tested (see Table 2 for a comparison of contraction types used across studies).

Larger studies in SAPS populations have since found no steadiness deficits in shoulder abduction (Camargo et al., 2009) or internal/external rotation (Zanca et al., 2010, 2013) compared to healthy control groups. By contrast, Overbeek et al. (2020), reported that SAPS patients actually demonstrated *greater* steadiness than healthy controls. This may indicate that individuals with SAPS have less motor options than healthy controls, resulting in a more predictable and therefore steadier torque output. Variability is increasingly seen as reflecting the adaptability of the motor control system, and research has shown that injured populations demonstrate less motor variability (Srinivasan & Mathiassen, 2012; Struyf et al., 2015; Wallwork et al., 2016). Further complicating this picture, Maenhout et al. (2012) found that accuracy and steadiness may be differentially affected in pathological populations, with rotator cuff tendinopathy patients showing altered matching accuracy but preserved steadiness raising the question of whether these components of torque control are independently sensitive to pathology. Taken together, these findings

suggest that if pain does disrupt torque control, this effect is neither consistent nor necessarily in an expected direction.

A recurring explanation across studies with null findings (Bandholm et al., 2006; Zanca et al., 2010, 2013), is that continued physical activity may preserve torque control mechanisms despite ongoing pain. Although this interpretation is coherent, it also reveals a more fundamental problem, as the role of training status and activity level on baseline torque control in non-elderly healthy populations has not been systematically examined (see Table 2 for study parameters). In athletic populations Zanca et al. (2013) found that asymptomatic athletes showed reduced internal rotation steadiness compared to non-athletic controls despite equivalent strength, suggesting that athletic training may affect torque control independent of pathology. Without a clearer understanding of what healthy torque control looks like across different activity levels, interpreting patient data remains inherently limited. In the absence of this evidence, accounting for activity level in participant selection represents a pragmatic approach to minimising its influence as a confounding variable.

Testing conditions represent another source of variance in results. The contrasting findings across isometric and dynamic conditions, both between and within studies, suggest that contraction type may be a meaningful moderator of steadiness. The variation in testing parameters across studies is summarised in Table 2.

Bandholm et al. (2008) provided one of the few direct comparisons of torque control under different contraction conditions (isometric versus concentric) in the same participants, revealing that healthy individuals respond differently to these conditions in the presence of experimentally induced pain. This suggests that isometric assessment of torque control may be more sensitive to change.

Similarly, Troussel et al. (2018) demonstrated that torque matching accuracy of the shoulder abductors in healthy shoulders varies with joint angle suggesting that torque control performance is position-dependent, possibly due to length-tension relationships of the involved muscles. Research in instability populations (Sacco et al., 2014) raised the possibility that testing position may mask genuine deficits. The authors suggested that the testing position of 90° glenohumeral abduction and external rotation may have facilitated adequate muscle activation, masking potential deficits, though this interpretation remains speculative and highlights the critical gap in understanding how testing position influences torque control performance in both healthy and pathological populations. That these methodological variables have not been standardised or systematically explored across the literature makes it difficult to determine whether inconsistencies in findings reflect genuine population differences or simply different testing protocols.

What the literature ultimately reveals is not that shoulder pathology does or does not impair torque control, but that the field lacks a sufficiently detailed understanding of healthy torque control against which pathological performance can be meaningfully compared. Until the parameters of healthy shoulder torque control are more comprehensively characterised, findings in pathological groups will remain difficult to interpret meaningfully.

The direction of movement varied across studies with internal rotation, external rotation, abduction, and adduction all examined, yet no research has systematically compared torque control across these different movement directions within the same healthy participants under controlled conditions. The finding by Zanca et al. (2013) that internal rotation showed different steadiness patterns than external rotation in athletes suggests direction-dependent effects, but whether this pattern exists in healthy non-athletic populations and what mechanisms underlie such differences remains unknown. This warrants further investigation as GHJ internal and external

rotation are of particular interest as they involve contribution from the rotator cuff in its stabilising role at the GHJ. Similarly, the distinction between agonist and antagonist muscle actions during different movement directions and how this influences torque control has not been explored. A torque tracking task requiring modulation of torque output between agonist and antagonist is one way that this could be investigated, but no study has investigated such a task at the shoulder. The type of muscle contraction has received minimal attention despite the contrasting findings between isometric and concentric conditions reported by Bandholm and colleagues. The literature contains no studies systematically comparing isometric, concentric, and eccentric contractions within the same healthy participants, and the single study that examined both concentric and eccentric contractions (Bandholm et al., 2006) did so only in a pathological population with a very small sample size. How contraction type fundamentally influences the neural control strategies and resulting steadiness and accuracy in healthy shoulders remains uncertain.

Nearly all studies provided continuous visual feedback during torque matching tasks, yet the role of visual feedback in shoulder torque control is poorly understood. Camargo et al. (2009) specifically noted that the provision of visual feedback may have facilitated performance and masked potential group differences in their pathology study. However, no research has systematically examined shoulder torque control in healthy populations with and without visual feedback to characterize the magnitude of this facilitatory effect or to understand the relative contributions of visual versus proprioceptive feedback to torque control performance. Given that many functional shoulder tasks occur without direct constant visual feedback, understanding torque control in the absence of visual feedback may be particularly relevant, yet this condition remains under investigated at the shoulder.

Target torque levels have varied widely across studies from 20% to 60% of maximum voluntary contraction, with different studies selecting different percentages

based on pragmatic concerns about fatigue rather than systematic investigation of how relative force level influences torque control. Whether torque steadiness and accuracy remain constant across different percentages of maximum effort or vary systematically with torque level in healthy shoulders has not been characterised, limiting the ability to interpret findings across studies or to optimize testing protocols.

Finally, the demographics of existing studies have been heterogeneous, including mixed age ranges, both athletic and non-athletic populations, and both genders, without systematic examination of how these demographic factors influence baseline torque control performance. The single finding that athletic status influenced torque control independently of pathology (Zanca et al., 2013) suggests these factors matter, yet comprehensive normative data accounting for age, sex, and training status in healthy young populations does not exist. Understanding the normal ranges and condition-dependent variations in torque control among healthy young individuals is necessary not only for interpreting pathology studies but also for understanding fundamental aspects of shoulder motor control, optimising rehabilitation protocols, and identifying individuals who may be at risk for injury due to poor motor control even in the absence of current symptoms.

As shown in Table 2, testing position, contraction type, movement direction, visual feedback conditions, and target torque levels varied considerably across studies, and none of these variables has been systematically investigated in healthy populations. This inconsistency is not merely a limitation of individual studies but a structural problem for interpreting the literature as a whole, since methodological differences are sufficiently large that conflicting findings between studies may reflect different testing protocols as much as genuine population effects. Positional variation is perhaps most consequential in this regard, given that the wide range of elevation angles, planes of movement, and joint positions employed across studies substantially alters the mechanical environment of the shoulder. Contraction type

and visual feedback conditions compound this further, as both influence the neural control demands of the task in ways that remain poorly understood even in healthy individuals. Without systematic investigation of these variables, it is difficult to determine whether inconsistencies across studies reflect true differences between populations or simply the influence of conditions that would produce different results in any cohort.

These inconsistent findings across the pathology literature and the limited research in healthy populations reveal several critical gaps in current knowledge that are particularly relevant to understanding torque control in healthy young cohorts. First and most fundamentally, nearly all existing research has been conducted in pathological populations with healthy controls included only for comparison purposes, meaning that the primary research objective has been to identify deficits rather than to systematically characterise normal torque control performance. This approach has left substantial gaps in understanding how various testing conditions influence torque control in the absence of pathology.

The following sections examine three conditions that may influence shoulder torque control; dual tasking, fatigue, and taping. Each represents a distinct mechanism through which the neural and mechanical demands placed on the sensorimotor system can be altered, with potential implications for shoulder function and injury risk. While dual tasking introduces competing cognitive demands that may disrupt attentional resources available for precise motor output, fatigue impairs the neuromuscular system's capacity to generate and regulate torque. Taping, by contrast, represents an intervention thought to modulate sensorimotor control through mechanical and neurophysiological pathways. Despite growing interest in each of these areas, their specific effects on shoulder torque control remain poorly understood, representing a significant gap in the current literature.

2.12 Dual Tasking

2.12.1 Introduction

Dual tasking is the simultaneous performance of two tasks, requiring co-ordination of attention between tasks (MacPherson, 2018). Studies of how performance of one task is impacted by performing a second task concurrently has been a mainstay of research in this field. Early investigations in the late 1990s and early 2000s demonstrated that walking and balance are not purely automatic motor processes but compete for attentional resources with concurrently performed cognitive tasks, with performance of one or both tasks frequently deteriorating under dual task conditions (Woollacott & Shumway-Cook, 2002). These foundational findings, largely derived from older adult and neurological populations, provided the impetus for researchers to broaden the scope of dual task paradigms beyond gait and balance into the musculoskeletal domain, where the interplay between cognitive load and motor performance is now recognised as relevant to injury risk and rehabilitation outcomes.

Within the health and rehabilitation literature, populations with an increased need for attentional resources for motor performance (and therefore decreased capacity for secondary task performance) have been of particular interest to researchers looking to improve health outcomes. For example, older adults (Bishnoi & Hernandez, 2021), people with neurological conditions (Fritz et al., 2015), and people following brain injury (Deblock-Bellamy et al., 2020). In more recent years, musculoskeletal rehabilitation researchers have started to investigate the role of neurocognition on injury risk, using dual task paradigms to explore concurrent motor and cognitive tasks relevant to sporting and real-world scenarios. Reyes et al. (2022) recently conducted a scoping review focused on cognitive function and lower extremity injury risk that included 13 studies explicitly looking at dual task paradigms. They reported that increased cognitive demand appears to be associated with altered lower limb

mechanics, that are thought to increase injury risk. More specifically, a direct increase in the rate of non-contact lower extremity injury was associated with poorer cognitive function (Wilke & Groneberg, 2022).

2.12.2 Dual Task Paradigms in the Musculoskeletal Context

Typically, musculoskeletal studies utilise motor-cognitive dual tasks and include functional tasks such as gait (Shi et al., 2021; Tavakoli et al., 2016), postural sway (Miko et al., 2021; Negahban et al., 2009; Rahnama et al., 2010; Watson et al., 2020) and jump-landing tasks (Dai et al., 2018; Schnittjer et al., 2021). Observed deficits of either motor and/or cognitive dual tasks in ACL populations has led to calls for more research in this area (Ness et al., 2020).

Dual tasking and sensorimotor control have been largely limited to kinematic variables as associated with gait performance (Plummer et al., 2016), jump-landing (Schnittjer et al., 2021), and cutting biomechanics (Norte et al., 2020). The effect on proprioception and sensorimotor control is less clear. Studies of the sensory components of sensorimotor control have largely used kinaesthesia and joint position sense (Chaput, Onate, et al., 2022; Jiang et al., 2023).

Divided attention during dual tasking has been found to impair trial-to-trial motor adaptation with a reaching task (J. A. Taylor & Thoroughman, 2007), although within-movement feedback control was not affected. Furthermore, in a cohort of healthy controls, reaction times to counteract passive knee movement, and threshold to detect passive movement were both impaired with the addition of a serial subtraction dual task, suggesting a retardation of proprioceptive information processing (Jiang et al., 2023). The importance of cognitive resources for proprioceptive function is further highlighted by findings in clinical populations. When comparing ACL reconstructed individuals with healthy controls, knee JPS did not differ significantly between groups; however, within the ACL group, higher visual memory scores were strongly correlated with more accurate JPS ($r=-.63$), a relationship absent in healthy

controls (Chaput, Onate, et al., 2022). Additionally, visual cognition was associated with increased neural activity in the precuneus and posterior cingulate cortex in the ACL group only. These findings suggest that individuals following ACL reconstruction may rely on visual cognitive processing as a compensatory mechanism to maintain neuromuscular control, in the absence of normal afferent input from the injured joint.

2.12.3 Dual Tasking and Torque Control

Studies of torque control under single and dual tasks are limited. In a cohort of young adult university students, Temprado et al. (2015) reported that finger abductor torque steadiness was impaired when performed concurrently with an auditory reaction task. This was significant at a 50%MVC target torque (Single vs Dual: $1.14 \pm 0.36\text{N}$ vs $1.33 \pm 0.53\text{N}$) but not at a 10% target torque ($0.36 \pm 0.08\text{N}$ vs $0.38 \pm 0.20\text{N}$). For both target levels, reaction time for the auditory task was significantly slower under dual task condition (50% 290ms; 10% 279ms) compared with the single task condition (264ms).

A series of studies by (H. M. Pereira et al., 2015, 2018, 2019) explored elbow flexor torque steadiness with the addition of a serial subtraction task. The first study (H. M. Pereira et al., 2015) found that higher cognitive demand from the subtraction task led to decreased torque steadiness, with older adults showing more pronounced changes than younger adults, especially at low (5%) target torques.

The second study (H. M. Pereira et al., 2018) investigated the role of executive function on age-related changes in low torque matching tasks, revealing that older adults were 35% slower on the trail-making test (a measure of executive function) and that executive function partly explained the decreased torque steadiness in older adults. The final study (H. M. Pereira et al., 2019) examined the role of common synaptic input using high-density surface EMG and found that oscillations in synaptic input were linked to reduced torque steadiness during the subtraction task, but only

in older adults and younger women, not younger men. The results of these studies (H. M. Pereira et al., 2015, 2018, 2019) indicate that oscillations in common synaptic input, and associated decreases in torque steadiness, can occur with the addition of a cognitive dual task. Muscle strength (MVC) differences, particularly those associated with older age, appear to influence greater oscillations in common synaptic input, and therefore decreased torque steadiness.

2.12.4 Summary

Dual tasking performance is becoming increasingly interesting to researchers in musculoskeletal medicine investigating sensorimotor control. However, knowledge in this area remains limited, and no studies to date have examined dual tasking and shoulder sensorimotor control. While research examining the effects of dual tasking on torque control remains limited, existing studies reveal important patterns regarding how cognitive load impacts motor steadiness, with the addition of a cognitive task consistently resulting in reduced steadiness (H. M. Pereira et al., 2015, 2018, 2019; Temprado et al., 2015). These findings indicate that the cognitive load imposed by dual tasking disrupts the neural resources required for precise torque control. Optimal task selection for both motor and cognitive tasks remain unclear, although task complexity and relevance should be considered when constructing a dual task paradigm. Measuring dual task effects of both constituent tasks is also recommended to understand performance changes and attentional resource allocation. The implications of these findings for the study design are discussed further in Chapter 3.

2.13 Fatigue

2.13.1 Introduction

Muscle fatigue is defined as the exercise-induced reduction in the maximal capacity to produce force (Vøllestad, 1997). Muscle fatigue has been identified as a significant risk factor for shoulder injury in sport (Eckard et al., 2018; Jones et al.,

2017; Kekelekis et al., 2020; Schwank et al., 2022; Tripp et al., 2007). Fatigue in muscles acting upon the GHJ may lead to reduced sensorimotor control, with resultant undesirable movement and forces occurring across the GHJ, predisposing to injury (Myers et al., 1999; Tripp et al., 2007). In overhead sports such as those involving the throwing action, the GHJ is exposed to high forces, necessitating sound sensorimotor control to co-ordinate movement and adequately disperse these forces. Similarly, in contact sports like rugby and wrestling, sensorimotor control is crucial in high-risk situations like the tackle (Burger et al., 2017; Davidow et al., 2020). Shoulder injuries have been shown to occur late in games of rugby (Burger et al., 2017) and wrestling (Goodman et al., 2018) when fatigue is a factor and loss of technique and sensorimotor control can expose the shoulder to injury risk.

2.13.2 Fatigue in the Musculoskeletal Context

Several studies have investigated the effect of muscular fatigue on aspects of sensorimotor control, including shoulder joint position sense (JPS) and kinaesthesia. Muscle fatigue has been demonstrated to significantly impair JPS (Iida et al., 2014; Lee et al., 2003; Myers et al., 1999) and threshold to detection of passive movement (TDDPM) (Carpenter et al., 1998). However, these findings have not always been consistently demonstrated with no significant effect found in other studies of JPS (Spargoli, 2017; Sterner et al., 1998) and TDDPM (Sterner et al., 1998). A recent meta-analysis of 12 relevant studies (Takasaki et al., 2016) reported that fatigue can have a deleterious effect on shoulder external rotation active repositioning acuity, with a standardised mean difference of -2.10° (95%CI: -2.57 to -1.63 , $p < 0.001$), although repositioning over other GHJ movements was not significant. This specificity of fatigue-related proprioceptive impairment to active JPS in outer ranges of external rotation suggests that the fatigue-proprioseption relationship at the shoulder is not a generalised phenomenon, but may reflect a movement/position specific susceptibility. This has direct implications for both the target musculature of

the fatigue protocol and the joint positions selected for sensorimotor assessment. The heterogeneity in fatigue definition observed across included studies, whilst limiting direct comparisons, highlights the need for an objective and quantifiable criterion that provides a physiologically meaningful threshold such as a drop in MVC or rating of perceived exertion. Finally, given that the majority of prior studies conducted post-fatigue testing within three minutes of task completion, the time-sensitive nature of fatigue-induced neuromuscular changes necessitates careful consideration of the post-fatigue testing window, to ensure that assessments are conducted whilst participants remain in a sufficiently fatigued state.

From an arthrokinematic perspective, fatigue of the shoulder muscles can lead to undesirable migration of the humeral head (measured radiographically) (S.-K. Chen et al., 1999; Chopp et al., 2010). Aberrant mechanics at the GHJ could predispose to the development of conditions such as subacromial pain syndrome in populations prone to shoulder fatigue such as in overhead sports, or with repetitive overhead work (Chopp et al., 2010). Additionally, it has been postulated that a loss of humeral head control can contribute to the development of acquired GHJ instability (Wang & Flatow, 2005), a non-traumatic instability associated with accumulation of structural microdamage due to repetitive overhead activity such as throwing.

Elsewhere, the evidence for fatigue-induced injury risk in the lower limb is conflicting due to significant differences in methodologies and difficulty synthesising data (Barber-Westin & Noyes, 2017; Santamaria & Webster, 2010). Sensorimotor deficits as evidenced by changes in kinetic and kinematic variables do appear to be present following fatigue. However, the relevance and implications of these findings remain unclear due to the inconsistent findings across studies with methodological issues such as a lack of direct measures of muscle fatigue, and limited reporting of effect sizes making it difficult to determine clinical relevance (Barber-Westin & Noyes, 2017).

2.13.3 Fatigue and torque control

Compared to kinematic assessment, torque control offers a more direct evaluation on the function of the sensorimotor system, and fatigue-induced changes on torque steadiness in particular have been well documented (Enoka & Farina, 2021; Pethick et al., 2021; Pethick & Tallent, 2022). For example, at the knee, fatigue has been demonstrated to reduce torque steadiness (CV) in young healthy adults following both maximal repeated concentric contractions (Wu et al., 2019), intermittent submaximal contractions (Pethick et al., 2015), and following repeated squat exercises (Singh et al., 2010).

The evidence for the effect of fatigue on torque matching accuracy, however, is mixed. Whilst torque steadiness decrements have been demonstrated with fatigue, Allison et al. (2016) found that torque matching accuracy (mean absolute error) was not impaired for either the knee flexors or extensors following a protocol of repeated maximal isokinetic contractions in a cohort of healthy young adults. This dissociation between steadiness and accuracy is theoretically meaningful. Steadiness is sensitive to peripheral neuromuscular noise and motor unit discharge variability, mechanisms that fatigue disrupts relatively consistently. Accuracy, by contrast, reflects the fidelity of matching a target, which is more dependent on the integration of afferent proprioceptive signals and efferent central commands. The apparent preservation of accuracy in the face of steadiness decrements at the knee may suggest that central representation of target torque remains intact even as the peripheral neuromuscular system becomes less capable of maintaining stable output around it.

However, this interpretation is complicated by findings at other joints. In contrast, repeated calf raises led to higher absolute (AE) and variable error (VE) in torque matching of the ankle plantar flexors (Vuillerme & Boisgontier, 2008). Another study at the ankle (C. J. Wright & Arnold, 2012) demonstrated increased AE, VE and CE for ankle evertors in individuals with and without ankle instability following

submaximal repeated concentric contractions. However, this finding was only observed with a 10% MVC target torque, whereas at 30% only VE increased with fatigue. The authors postulated that at higher MVC, more motor units are recruited and therefore more proprioceptive mechanoreceptors are stimulated providing more sensory feedback. However, this hypothesis remains to be tested.

The dependence of accuracy decrements on target torque level has direct implications for understanding fatigue effects at other joints. If proprioceptive afferent input magnitude moderates accuracy, with lower torques providing insufficient sensory signal under fatigue, then target torque selection fundamentally shapes study outcomes, not merely as a methodological detail, but as a key variable. Studies using moderate or high target torque may fail to detect accuracy impairments that may be present at lower torque levels, and vice versa. Thus, null findings in accuracy tasks require careful consideration of the target torque. Whether the same torque accuracy relationship observed at the ankle exists at the shoulder remains unclear. The glenohumeral joint's greater sensory redundancy, spanning capsular and muscular mechanoreceptors across a complex rotator cuff, may attenuate this effect, but this has yet to be established.

In the upper limb, torque matching deficits at the elbow have been consistently observed following fatiguing eccentric exercise (Brockett et al., 1997; Carson et al., 2002; Proske et al., 2004) and sustained submaximal isometric contractions (Brooks et al., 2013). These studies used a contralateral limb matching task, requiring participants to reproduce a target force in the rested limb using information about the perceived effort of the fatigued limb; any error therefore reflects distortion in the central sense of effort rather than a failure of peripheral proprioception. By contrast, in ipsilateral matching tasks the participant matches to a remembered target using feedback from the same limb. These two paradigms therefore assess fundamentally different aspects of the sensorimotor system. For the shoulder, this has practical

implications as studies that elect to use a contralateral design would be measuring the effect of fatigue on central representations of effort, while ipsilateral tasks would more closely reflect the integrity of peripheral afferent pathways from the rotator cuff muscles and glenohumeral capsule. Given that shoulder pathology such as rotator cuff tears and instability often disrupts local afferent pathways, an ipsilateral design may have greater clinical relevance, though it must be acknowledged that central fatigue mechanisms are also likely involved at the shoulder. Taken together, the evidence suggests that neither steadiness nor accuracy should be assumed to behave uniformly across joints or conditions.

Only one study has examined fatigue effects on shoulder torque control. Coskun et al. (2018) found no effect of a maximal isokinetic fatiguing protocol on isometric torque matching accuracy at 50% MVC in healthy young males, for either internal or external rotation, with or without visual feedback. However, the study has significant limitations. Fatigue was not verified beyond the end of the fatiguing protocol, and given the duration of post-fatigue testing, with all visual feedback trials completed before no-feedback trials, it is unclear whether participants remained sufficiently fatigued during testing. Torque steadiness was not assessed.

As with the ankle literature, accuracy impairments may be target-torque dependent; 50% MVC may have provided sufficient proprioceptive afferent input to maintain matching performance even under fatigue, and a lower target torque may have yielded a different outcome. The absence of fatigue verification means the study cannot determine whether the null finding reflects genuine resilience of shoulder proprioception to fatigue, or simply recovery prior to testing.

The study therefore demonstrates only that torque matching accuracy at 50% MVC is not detectably impaired following maximal isokinetic shoulder rotations in healthy young men under conditions of uncertain fatigue state. Whether accuracy at lower

torque targets is similarly robust, whether steadiness is preserved, and whether findings generalise beyond this sample remain unanswered.

2.13.4 Summary

Muscle fatigue is a significant injury risk factor, particularly at the shoulder where it may impair sensorimotor control. Torque control offers a direct evaluation of sensorimotor function, with fatigue-induced decrements in torque steadiness consistently documented across various joints including the knee and elbow following maximal and submaximal contraction protocols. However, evidence regarding fatigue's effect on torque matching accuracy is mixed, with some studies demonstrating impairments at the ankle and elbow whilst others, including one at the knee, showing no deficits. Surprisingly, only one study has investigated fatigue and torque control at the shoulder, with Coskun et al. (2018) finding no effect of isokinetic fatigue on torque matching accuracy, though this study had methodological limitations including lack of fatigue confirmation during post-fatigue testing and no examination of torque steadiness. Most shoulder fatigue research has employed maximal isokinetic protocols with conflicting kinaesthetic proprioceptive results. Intermittent submaximal isometric tasks have recently gained popularity as they reduce vascular occlusion effects, are easier to standardize, more closely represent daily muscle activation patterns, and induce significant fatigue efficiently when performed with sufficient intensity. Methodologically robust investigation, with confirmed fatigue states, theoretically selected target torques, and both accuracy and steadiness measures, is needed. The implications of these findings for the study design are discussed further in Chapter 4.

2.14 Taping

2.14.1 Introduction

Taping is often used in athletic and clinical environments for injury rehabilitation and prevention especially where a high risk of injury may exist. Despite a lack of clear

efficacy in (re)injury prevention, it's widely believed that shoulder taping has clinical benefits hence, its continued and prevalent use, particularly in high-risk environments such as overhead (Asker et al., 2018; Borsa et al., 2008) and contact sports (Arner et al., 2022). These sports expose the shoulder to high training loads and stresses, with resulting undesirable adaptations such as reduced passive GHJ stability, muscle imbalances, and scapula dyskinesis (Borsa et al., 2008). Taping is therefore a clinically valued intervention for clinicians to try and mitigate these adaptations and injury risks (Turgut et al., 2023).

If taping increases afferent input to the CNS as postulated, it could theoretically improve motor responses to perturbations in healthy individuals, thereby enhancing dynamic torque control during tasks requiring rapid adjustments. Some support for this hypothesis comes from studies at the ankle, where rigid taping has been shown to increase peroneal EMG activity compared to kinesiology tape and no tape in healthy participants (Briem et al., 2011) and to produce greater peroneal activation per degree of inversion during simulated sprain compared to no taping (Alt et al., 1999; Lohrer et al., 1999).

2.14.2 Taping in the Musculoskeletal Context

Several mechanisms concerning the effect of taping have been proposed, including ROM limitation (McConnell et al., 2011), psychological benefit (Delahunt et al., 2010), and improvement of proprioception and sensorimotor control (Morrissey, 2000; Snodgrass et al., 2018).

From the sensorimotor control perspective, a review of 50 studies into the effect of joint stabilisers on proprioception (Ghai et al., 2017) included a total of 14 studies that explored taping. These studies assessed effects at joints including the shoulder, knee, and ankle. The authors argued that the overall results of their meta-analysis supported the use of joint stabilisers for both prophylactic use and rehabilitation, based on evidence to support mechanical stabilisation, central cortical changes, and

changes to muscle activation. Specifically, the meta-analysis for pooled studies of taping demonstrated a small negative effect on active JPS at the knee of individuals with patellofemoral pain (95%CI: -0.35° to 0.15° ; $g=-0.10$) and a positive at the ankle in those with ankle instability (95%CI: 0.08° to 0.43° ; $g=0.26$). The clinical relevance of these relatively small changes is debatable.

More recently, a review (Turgut et al., 2023) of shoulder taping in overhead athletes found limited to moderate evidence to support the use of taping for limiting ROM, improving scapula kinematics and proprioceptive enhancement. However, the evidence did not support taping for effects on muscle strength, changes in muscle activity, nor measures of functional performance.

2.14.3 Taping and Torque Control

Whilst several studies have explored the theory that taping can improve proprioceptive acuity, these have largely been limited to studies examining joint position sense (JPS) (Ager et al., 2023). In contrast, few studies have examined taping and torque control measures. A recent systematic review and meta-analysis (Ghai et al., 2023) identified only 11 studies, six at the wrist and five at the ankle. From the results of their meta-analysis, the authors concluded that elastic tapes significantly improved absolute torque matching accuracy ($p=0.009$, $g=-0.76$), whereas, based on only two studies, rigid tape did not ($p=0.069$, $g=-0.82$). However, this effect size is large, and the p-value was close to significance. In the context of the meta-analysis, this most likely means the small number of pooled studies and small combined sample sizes led to under-powered results. This suggests the effect may be real and clinically meaningful, but the current evidence base is too limited to confirm this statistically. The two studies which included rigid taping are described in more detail below.

Hopper et al. (2014) tested the effects of rigid ankle taping on torque matching accuracy in healthy young women, finding no significant effect on absolute torque matching error of the ankle plantar flexors (no taping 1.3 ± 0.8 kg; taping 0.9 ± 0.5 kg). Within a clinical population, taping and wrist extensor torque matching has been compared in individuals with tennis elbow and an uninjured control group (Lee et al., 2011). While taping improved torque matching accuracy in the tennis elbow group (1.24 ± 0.48 kg vs 0.49 ± 0.32 kg, $p < 0.01$), no effect was observed in the healthy control group (0.48 ± 0.31 kg vs 0.43 ± 0.21 kg). At the shoulder, no studies have examined taping and torque matching accuracy. Furthermore, no studies have explored the effect of taping on torque steadiness measures at any joint.

2.14.4 Summary

Taping is often used in athletic and clinical environments for injury rehabilitation and prevention, particularly in high-risk environments such as overhead and contact sports where the shoulder is exposed to high training loads and stresses. Several mechanisms concerning the effect of taping have been proposed, including ROM limitation, psychological benefit, and improvement of proprioception and sensorimotor control. Recently, a review of shoulder taping in overhead athletes (Turgut et al., 2023) found limited to moderate evidence to support the use of taping for limiting ROM, improving scapula kinematics and proprioceptive enhancement.

Whilst several studies have explored the theory that taping can improve proprioceptive acuity, these have largely been limited to studies examining joint position sense, with few studies examining taping and torque control measures. A recent systematic review and meta-analysis (Ghai et al., 2023) identified only 11 studies, concluding that elastic tapes significantly improved absolute torque matching accuracy, whereas rigid tape did not, although the results for rigid tape were likely underpowered due to only two studies being included in the pooled data.

Thus, taping may influence torque control through enhanced cutaneous mechanoreceptor feedback, altered muscle activation patterns, and improved motor response timing, though evidence for each mechanism remains inconsistent and no studies have examined these effects specifically at the shoulder. The implications of these findings for the study design are discussed further in Chapter 5.

2.15 Overall Summary

Throughout the literature on shoulder rehabilitation and injury prevention, the importance of adequate sensorimotor control is pervasive. However, there remain significant gaps in the knowledge base on what aspects of sensorimotor control are of most importance and are amenable to change. Studies using torque control methods are one way for researchers to make inferences about sensorimotor function, and the body of research in this area is growing, especially within the injury prevention and rehabilitation space. Even so, there is still a dearth of studies at the shoulder, despite its inherent reliance on muscle activity for stability, high rates of injury, and the individual and societal burden associated with significant shoulder injuries. Furthermore, growing understanding of torque control measures and their association with performance and functional measures has the potential to improve rehabilitation and injury prevention strategies.

The effect of injury on torque control measures is an evident focus of research, but questions remain on how torque control is influenced by other factors in the healthy shoulder. Specifically, it remains to be seen if shoulder submaximal torque control is enhanced with taping, or detrimentally affected by fatigue, as has been observed with other measures of sensorimotor control and at other joints. Musculoskeletal research into sensorimotor control and dual tasking is emerging with little known of the dual task effect on measures of torque control especially at the shoulder. The following chapters report the results of three studies of torque control at the shoulder in a healthy cohort of young adults under varying conditions, namely, 1) motor-

cognitive dual tasking, 2) muscle fatigue, and 3) shoulder taping. Each chapter further explores the literature of torque control studies specific to each topic to provide the greater insight into the relative importance of torque control at the shoulder.

Introduction to Experimental Chapters

Introduction

The preceding chapters established a need to investigate aspects of shoulder sensorimotor control, notably assessment of local shoulder muscle torque control.

The following experimental chapters address this by investigating shoulder internal and external rotator torque control in a healthy cohort under different conditions.

This programme of research was designed and conducted during a period of significant disruption caused by the COVID-19 pandemic. The studies presented here were originally conceived as investigations involving a cohort of individuals with traumatic shoulder instability and uninjured individuals, across more testing sessions. However, the extended public health restrictions in Auckland from March 2020 through to December 2021 necessitated a fundamental reconsideration of this approach. This required further ethics applications and approval, hence the working title changes evident in the ethics correspondence in Appendices B & C.

Methodological Adaptations

Four interconnected factors shaped the revised study design. First, ethical concerns about participant burden during healthcare system strain. Second, the risk that ongoing restrictions would result in incomplete data collection. Third, constrained laboratory access due to reduced availability and competing demands from delayed research programmes. Finally, potential recruitment challenges due to severely impacted sports participation and therefore reduced new shoulder injury incidence. Together, these factors necessitated a shift in focus to healthy participants rather than clinical populations.

Given constraints on laboratory access and the necessity to minimise participant visits, a degree of participant overlap across studies was incorporated into the design. For the dual task study, all participants were unique and none had taken part

in any pilot work. For the fatigue and taping studies, a proportion of participants (n=6; 30%) had previously participated in the first study. However, the data collection sessions were separated by several months representing a time frame that makes a learning effect negligible. This approach reduced the overall recruitment burden and made efficient use of limited laboratory time. Across all three studies, 34 unique participants contributed data.

The persistent uncertainty regarding future restrictions also influenced the sequencing of data collection. Rather than conducting the studies sequentially (which would have been the conventional approach and would have allowed findings from earlier work to inform later protocols) data for Chapters 4 and 5 were collected concurrently within a single laboratory session. Relatedly, this necessitated a weaker study design for the fatigue study. Concurrent collection ensured that each participant visit yielded complete data for multiple research questions. The taping condition was investigated initially followed by a break of 30 minutes, and then the fatigue condition was subsequently investigated. Randomisation of the order of tasks in the taping study helped to mitigate for order effects, and any learning effect was deemed unlikely to affect the results of the fatigue study. Order and learning effects are discussed as potential limitations within the relevant chapters.

These adaptations represent considered compromises rather than ideal design choices. The studies that follow should be interpreted with this context in mind, and the implications of these methodological decisions are revisited in the discussion sections of each chapter and in the final thesis discussion.

Chapter Overview

The following chapters present the experimental work. Each chapter provides an introduction reporting the relevant background, aims and methodological considerations for the study. Methods, results, and discussion are then presented before a conclusion and future recommendations. Chapter 3 explores shoulder

torque control in healthy participants under single and dual task conditions. Chapter 4 then investigates the effect of muscle fatigue on shoulder torque control in a similar young healthy cohort. Chapter 5 then examines the potential effects of a clinical taping application on shoulder torque control in the same cohort. Finally, Chapter 6 presents a discussion of the overall results and limitations of the experimental chapters with recommendations for future research.

Chapter 3: The Effects of Dual Tasking on Submaximal Torque Control at the Shoulder

3.1 Introduction

There remains a lack of high-quality evidence to guide shoulder injury prevention (Schwank et al., 2022) and the effectiveness of injury prevention programs has also been called into question (A. A. Wright et al., 2021). Across the injury prevention literature, most interventions have focused on biomechanical and physical performance traits such as maximum strength, strength ratios, and isolated movement performance. Whilst there is evidence of varied quality for these factors, the seemingly poor 'return on investment' seen in respect of injury rates has led to researchers exploring new paradigms. Most notably, the role of neurocognition has garnered increasing attention (Grooms et al., 2015; Needle et al., 2017; Walker et al., 2021; Wilk et al., 2023), with the realization that traditional metrics are not sufficient in fully assessing an individual's preparedness for participating in some sporting environments, particularly those which are inherently dynamic and chaotic in nature.

Dual tasking is a paradigm that can be utilised to assess neurocognition in tandem with motor task performance. It assesses the ability to perform both tasks simultaneously and reflects a measure of executive function as it relies on an individual's ability to co-ordinate attention between tasks (MacPherson, 2018). Task interference occurs when simultaneous performance results in decrements in performance of one or both tasks. The musculoskeletal literature highlights the impact of motor-cognitive dual tasks on functional motor tasks such as gait (Shi et al., 2021; Tavakoli et al., 2016), postural sway (Miko et al., 2021; Negahban et al., 2009; Rahnema et al., 2010; Watson et al., 2020) and jump landing tasks (Dai et al., 2018; Schnittjer et al., 2021). A recent scoping review that included 13 studies of dual task performance (Reyes et al., 2022) explored how additional cognitive

demand affects lower extremity injury risk. All the dual task studies consistently demonstrated a dual task effect, with altered lower limb mechanics in a manner that could increase the risk of injury.

Dual task performance can be measured for both tasks to ascertain a dual task effect (DTE) (Plummer & Eskes, 2015). This allows researchers to examine the interaction between the cognitive and motor tasks and how individuals prioritise their attention, giving insight into strategies used for dual task performance. Underlying mechanisms of dual task interference are not fully understood; however, three proposed models are prevalent in the literature: the central capacity sharing model (Tombu & Jolicoeur, 2003), the bottleneck model (Pashler, 1994) and the multiple resources model (C. D. Wickens, 1980).

The central capacity theory posits that cognitive resources are finite and can be divided between several tasks simultaneously as needed (Tombu & Jolicoeur, 2003). Parallel processing of tasks therefore can lead to performance decrements as concurrent tasks compete for the same resources. In contrast to parallel processing, the bottle neck theory proposes that at crucial processing stages only one task can be processed at a time (Pashler, 1994) with a delay/degradation in performance of the task waiting to be processed. C. D. Wickens (1980) proposed the multiple resources model suggesting several independent resource pools dependent on the stimuli being processed. When two tasks are competing for the same resources, the interference in individual task performance is greatest, with less interference when the tasks require different resource pools. Contemporary research suggests a hybrid model with neither serial nor parallel processing occurring strictly in isolation (Leone et al., 2017; Schuch et al., 2019).

The brain operates with limited processing capacity, and cognitive tasks compete with motor control for shared neural resources, particularly in prefrontal and parietal

cortices which manage concurrent task execution (Leone et al., 2017). This competition is mediated by overlapping neural networks in regions like the dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC), which serve both executive and sensorimotor functions (Diamond, 2013; Freedman & Ibos, 2018; Funahashi, 2017; Kane & Engle, 2003; Whittier et al., 2023). When cognitive demands increase, attentional resources may be diverted away from motor planning and execution, resulting in performance decrements in one or both tasks.

Concurrent performance of torque control and cognitive tasks introduces both central and structural interference. Central interference arises from competing demands for shared attentional resources in overlapping neural networks, particularly in the DLPFC and PPC (Freedman & Ibos, 2018; Leone et al., 2017; Pashler, 1994). When both tasks require visual input processing, structural interference compounds this effect through competition for visual processing pathways (Worden et al., 2016). While no single brain locus for dual-task interference has been identified, existing literature suggests dual-tasking involves dynamic interactions between distributed brain networks (Leone et al., 2017). This dual mechanism of interference provides a strong rationale for investigating dual-task effects on shoulder torque control.

Understanding these dual-task effects in healthy populations is important for injury prevention and performance optimisation. In real-world scenarios, athletes and workers rarely perform motor tasks in isolation; rather, they must maintain torque control while simultaneously processing environmental information, making tactical decisions, or responding to cognitive demands. For instance, overhead athletes must regulate shoulder forces while tracking game dynamics, and manual labourers must maintain safe lifting mechanics while attending to workplace hazards. If cognitive load is deleterious to torque steadiness or accuracy in healthy individuals, this could compromise joint stability and increase injury risk during situations where attentional demands are elevated.

Moreover, given that torque steadiness and proprioception share prefrontal resources with working memory and attention, baseline data from a healthy cohort may reveal which aspects of sensorimotor control are most susceptible to cognitive interference. Such knowledge could inform targeted interventions, such as dual-task training protocols, to improve motor-cognitive dual task performance, potentially reducing injury risk when athletes or workers face complex, attention-demanding environments.

Task prioritisation is a critical concept in motor-cognitive dual-tasking research, referring to how individuals strategically allocate limited attentional resources between concurrently performed motor and cognitive tasks as an adaptive response to competing processing demands (Yogev-Seligmann et al., 2012). This reflects greater attentional resources devoted to one task preferentially over another, which can improve performance on the prioritised task during dual-tasking (Jansen et al., 2016). Not instructing a participant on prioritisation and measuring performance change across both tasks allows inferences to be made about how an individual prioritises tasks for allocation of attentional resources, and how task complexity may influence that prioritisation (Plummer & Eskes, 2015; C. Wickens, 2021).

In the extensive literature on motor-cognitive dual tasking, the cognitive tasks used vary widely with the choice of task dependent on the population, the goals and the methodology. In a review of studies of motor-cognitive dual tasking in injured populations (Burcal et al., 2019) the majority of studies used numerical cognitive tasks (e.g. memorisation and counting). Whilst relatively easy to implement, they rely on participant numeracy skill and also may not provide sufficient challenge. Tasks with a visual component introduce more competition for visual processing resources more representative of real-world scenarios (Burcal et al., 2019; Worden et al., 2016). Similarly, tasks that require higher executive function offer a more realistic cognitive challenge.

Combining both visual processing demands and executive function requirements, as in a visual Stroop task, creates both structural and central interference, maximising cognitive-motor dual task interference. The Stroop effect refers to the interference that occurs when processing conflicting incongruent information. For example, in the original colour-word task described by Stroop (1935) the name of a colour is presented in an ink of a different colour requiring inhibition of the automatic response (reading the word) in favour of the task-relevant response (naming the ink colour).

Several versions of tasks that induce a Stroop effect have been described throughout the literature including auditory tasks and spatial tasks, but they are designed to induce the same Stroop effect but using different congruent and incongruent stimuli (MacLeod, 1991).

In a previous study of dual-tasking during gait (Patel et al., 2014), a Stroop task was utilised to induce greater motor performance decline compared to a simpler reaction time task. This result showed that when a cognitive task requires executive function and planning, the cost to motor performance is increased in order to preserve performance of the cognitive task.

As previously mentioned, the majority of motor-cognitive dual tasks utilise motor tasks related to postural control or gait. These have ecological validity, but the motor tasks involved present many confounding variables such as anthropometric differences, environmental considerations (e.g., footwear and surfaces), and degrees of freedom with multiple movement options available in multi-joint tasks. Experiments utilising sensorimotor tasks allow for more precise quantification of motor performance with fewer confounding variables, making them valuable for understanding fundamental mechanisms of dual task interference on sensorimotor mechanisms.

Torque steadiness and accuracy rely on sensorimotor pathways with shared cortical regions associated with cognitive tasks (Li et al., 2025; N. S. Ward & Frackowiak, 2003). Torque steadiness refers to the ability to maintain a constant submaximal force output with minimal fluctuations, typically quantified as the standard deviation (SD) of torque over time, with lower SD values indicating steadier, more stable torque production (Enoka et al., 2003; Slifkin & Newell, 1999). Torque matching accuracy refers to how precisely an individual can match or track a target torque level, typically quantified as root mean square (RMS) error between actual and target force, with lower RMS values indicating more precise torque control (Schmidt et al., 2018). These measures provide information about sensorimotor control of torque production. Studies have shown that dual task conditions affect torque steadiness in younger adults, notably at the finger (Temprado et al., 2015) and elbow joints (H. M. Pereira et al., 2015, 2018, 2019). Specifically, research demonstrates reduced torque steadiness under dual task conditions, such as when performing an auditory reaction task (Temprado et al., 2015) or mental arithmetic (H. M. Pereira et al., 2015, 2018, 2019).

Whilst these studies demonstrated that the addition of cognitive load through dual task performance led to decreased torque steadiness in young adult cohorts, there have been no studies exploring the effects of dual tasking on torque control at the shoulder. In addition, the studies that have been completed at other joints utilised a relatively simple torque matching task. Using a more complex torque tracking task may be more representative of muscle force grading required for functional movement (S. H. Ward et al., 2019). Given the aims of this thesis, the glenohumeral joint warrants specific investigation as overhead athletic and occupational activities require continuous torque modulation while processing environmental information; contexts where injury might occur due to impaired torque steadiness and/or accuracy under cognitive load. It would be of interest to examine whether dual task

interference manifests differently during static torque maintenance versus dynamic torque tracking, as real-world shoulder control demands both sustained stability and adaptive torque modulation.

3.1.1 Aims

The primary aim was to assess the effects of the addition of a visual-cognitive (Stroop) task on torque control at the shoulder. Torque steadiness and accuracy were examined during 1) a torque matching task and 2) a torque tracking task, under single and dual task conditions. We hypothesised that, under dual task conditions with a visual-cognitive Stroop task: 1) shoulder internal and external rotation torque matching steadiness would decrease (reflected by increased SD), and torque matching accuracy would decrease (reflected by increased RMS); 2) torque tracking accuracy would decrease (increased RMS); and 3) Stroop task performance would decrease with reduced response accuracy and increased reaction time compared with single task conditions. Previous research (Zijdewind et al., 2006) has demonstrated that motor tasks with higher demand lead to greater dual task effects when compared with lower demand tasks. We therefore anticipated that 4) dual-task interference would be greater during the torque tracking task compared with the torque matching task (indicated by greater decrements in torque matching accuracy), given the increased attentional demand for continuous torque modulation compared to the static torque matching task.

3.2 Methodological Considerations

Before describing the specific methods for this study, an overview of the key methodological considerations for measuring torque control and implementing dual-task paradigms is presented. The following sections address decisions regarding instrumentation, testing parameters, task design, and dual-task implementation that informed the methodological approach of this study.

3.2.1 Isometric peak torque

To assess torque control, tasks need to be performed at an appropriate relative torque level. To establish a relative percentage target torque, an individual's maximum isometric torque needs to be established. Isometric peak torque is particularly useful as it enables researchers and clinicians to easily measure maximum force production across a joint in stable positions and with high levels of reliability.

While various methods exist for measuring peak torque, an isokinetic dynamometer is considered the gold standard due to its high reliability and validity. Previous research has shown the excellent reliability of the Biodex 3 system (Biodex Medical Systems, Shirley, New York, USA) in measuring isometric torque for both research and clinical purposes (Drouin et al., 2004), where intraclass correlation co-efficient (ICC) scores were 0.99 for trial-to-trial and day-to-day reliability. Additionally, the largest coefficient of variation of measurement error between the system torque and criterion torque was 1%, suggesting any discrepancy is negligible.

Specifically at the shoulder, isometric testing of shoulder internal and external rotation in abduction in the scapula plane was found to have good to excellent reliability with an ICC ranging between 0.81 and 0.93 (Malerba et al., 1993) and between 0.75 and 0.86 in the unaffected limb in a population with chronic rotator cuff pathology (Anderson et al., 2006). In a recent systematic review (Sørensen et al., 2021) of isokinetic dynamometer assessment of shoulder muscle strength, the conclusion was that of satisfactory reliability across positions and modes and velocities of strength assessment.

Assessing torque control requires establishing individual maximum isometric torque to determine appropriate relative percentage targets. The Biodex 3 isokinetic dynamometer was selected based on its excellent reliability for measuring isometric

shoulder torque, particularly internal and external rotation assessment in the scapula plane.

3.2.2 Tasks

As discussed in Chapter 2 (Sections 2.9.2-2.9.4), static torque matching and torque tracking tasks each provide distinct insights into sensorimotor function, and together offer a more comprehensive assessment of torque control than either alone.

Ipsilateral static torque matching tasks assess an individual's ability to reproduce a target torque. generated from the same limb, relying on working memory and peripheral afferent feedback from muscle spindles and Golgi tendon organs (Jami, 1992; Proske & Allen, 2019). This approach is preferable over a contralateral limb matching task, having greater functional relevance as we typically use limbs independently to achieve external goals rather than comparing efforts between sides.

Real-world motor control rarely involves producing a single steady force; instead, torque must be continuously modulated. Torque tracking tasks therefore address a key limitation of static matching and better approximate everyday function. Relatedly, they uniquely assess CNS systems involved in grading torque production, including how real-time prediction and feedback influence motor control (Huang et al., 2014; R. Jones, 1999).

Examining both task types therefore provides complementary insights. Static matching isolates the ability to perceive and reproduce a discrete force level, while tracking tasks capture dynamic modulation, feedforward planning, and feedback correction that characterise functional movement. Together, they examine sensorimotor function from peripheral sensation and memory through to predictive control and real-time adjustment.

Good to excellent reliability of shoulder torque matching tasks have previously been established with an ICC of 0.849 and 0.909 for internal and external rotation torque matching accuracy respectively (Maenhout et al., 2012). Furthermore, from the pilot work collected in our lab (n=6), excellent test-retest reliability was established for torque matching steadiness (SD) ICC=0.95, 95%CI [0.66,1.00]; and for torque matching accuracy (RMS) ICC=0.99, 95%CI [0.92,1.00].

Data of torque tracking accuracy tasks is limited but excellent trial-to-trial reliability has previously been demonstrated for a waveform hand grip torque tracking task in healthy subjects with an ICC 0.95 (Nagasawa et al., 2003). From separate pilot data (n=6) prior to this study, good to excellent reliability for torque tracking accuracy (RMS) was established ICC=0.96, 95%CI [0.87, 0.99].

3.2.3 Target torque levels

In Chapter 2 (section 2.9.3), the effect of target torque magnitude on steadiness was discussed with targets of <10% and >50% MVC resulting in reduced torque steadiness (Enoka & Farina, 2021). Previous work at the shoulder, whilst divergent in target torques used, typically uses targets between 20 and 60% MVC.

Furthermore, an in vivo study of rotator cuff muscle contraction and GHJ translation in the apprehension position demonstrated rotator cuff EMG activity between 30-55% for subscapularis and 30-50% for infraspinatus (Rathi et al., 2016). This was in keeping with reported cuff activity levels across different GHJ positions presented in a previous systematic review (Sangwan et al., 2015). These activation levels correspond to functional demands during activities of daily living and overhead tasks, including reaching, lifting, and stabilisation during throwing motions.

For a static torque matching task, a target torque of 35% MVC was chosen. This represents an appropriate magnitude given precedence in previous studies, documented rotator cuff activity with typical functional tasks, levels of activity observed when resisting perturbing forces at the GHJ. Similarly, for a torque tracking

task a range of targets from 10-60% MVC requires modulation of torque through a range representative of rotator cuff activity observed in the literature.

3.2.4 Shoulder testing position

Shoulder strength measures, proprioception, and torque control have been assessed in numerous positions and across many studies (Ager et al., 2017; Edouard et al., 2011). Some authors have proposed that testing shoulder muscle function in the scapula plane is desirable, as it provides optimal joint congruence, reduces stress on capsuloligamentous structures, and establishes favourable length-tension relationships for the cuff muscles (Kramer & Ng, 1995; Mandalidis et al., 2001). However, evidence from other peripheral joints has demonstrated conflicting effects of muscle length on torque steadiness. For example, at the knee, joint angle was observed to alter quadriceps torque variability, with greater torque fluctuations demonstrated at 90° compared to 30° of knee flexion (i.e., increased quadriceps length) (Krishnan et al., 2011). Conversely, at the wrist, joint angle did not affect torque steadiness for the wrist flexors (Salonikidis et al., 2009).

Given the heterogenous approach to position in shoulder testing (see section 2.11.1, p.56) and the conflicting evidence regarding the effect of joint angle on torque control, testing position may best be guided by clinical relevance. A commonly used position for functional assessment with clear clinical implications is the apprehension position, where the glenohumeral joint is positioned in >60° of abduction and >60° of external rotation. This position holds functional importance for overhead activities where arm elevation requires significant amounts of GHJ abduction elevation and external rotation (Inui et al., 2009; Stokdijk et al., 2003) as well as more complex limb movements such as throwing where the shoulder is 'cocked' to enable force generation and transfer. Jobs that entail working with the arm in the elevated/overhead positions (thus approximating the apprehension position) have been associated with higher risk of shoulder injury (Wærsted et al., 2020), and

similar elevated/rotated positions are also associated with injury risk in athletic populations (Salamh et al., 2025).

Previous studies have demonstrated the stabilising effect of the rotator cuff, particularly the subscapularis, in positions approaching end range more so than during mid-range positions (Labriola et al., 2005; S.-B. Lee et al., 2000; Sangwan et al., 2015). Additionally, as the GHJ approaches end range positions, there is corresponding increases in capsuloligamentous tension particularly of the IGHL and axillary pouch (Bigliani et al., 1996). Increasing tension in these structures is associated with changes in joint position sense through posited increases in mechanoreceptor activation (Diefenbach & Lipps, 2019). Existing studies of torque control at the shoulder have utilised different shoulder testing positions (Chapter 2 Section 2.11.3). However, only one study (Trousset et al., 2018) has examined the effect of GHJ position on torque control finding less abduction torque RMS error (i.e. greater accuracy) at lower (50°) compared with higher (90°) elevations in the scapula plane.

In summary, testing position requires careful consideration; whilst elevations in the scapula plane offer optimal joint congruence and favourable length-tension relationships for rotator cuff muscles, the apprehension position (>60° abduction and external rotation) may be more clinically relevant for overhead activities and has been associated with increased rotator cuff stabilisation demands and capsuloligamentous tension.

3.2.5 Limb Dominance

Research suggests that limb dominance does not significantly affect shoulder rotation peak torque measures (Otis et al., 1990), handgrip torque steadiness (R. Pereira et al., 2012), or shoulder active and passive angle reproduction (Voight et al., 1996). A review of upper limb asymmetries in sensorimotor performance (Goble & Brown, 2008) demonstrated that dominant and non-dominant arms appear to rely

differentially on visual and proprioceptive feedback based on task-specific preference use of their arms. The preferred (typically dominant) arm shows advantages in trajectory control utilising visual feedback, while the non-preferred (typically non-dominant) arm is better at positional control and using proprioceptive feedback-dependent tasks. Controlling for handedness through randomisation therefore may prevent these asymmetries from systematically biasing study findings. It may also be preferable to randomise the limb for testing as this helps findings generalise more broadly to sensorimotor processing as a whole rather than specifically to dominant upper limb function.

Hence, either selecting or randomising the limb to be tested could be considered appropriate. Given that limb dominance does not significantly affect shoulder peak torque or proprioceptive accuracy measures, yet dominant and non-dominant arms rely differentially on visual versus proprioceptive feedback, randomising the tested limb would prevent these asymmetries from systematically biasing results and improve generalisability to sensorimotor processing overall. Conversely, selecting the dominant limb can be beneficial when considering including interventions that demonstrate limb dominance differences and/or when there is previous research for comparison and there is precedence for limb selection.

3.2.6 Cutaneous sensory influences

The Biodex 3 upper limb attachment has a handle for participants to grip when performing shoulder muscle contractions. Whilst convenient, this poses a potential limitation about the role of tactile sensory feedback at the hand when performing torque control tasks designed to assess torque control across the glenohumeral joint. Early work by Gandevia & McCloskey (1977) found that when a weight was lifted by the thumb, it felt heavier when the cutaneous afferents were anaesthetised. Given that the hand is densely innervated with mechanoreceptors (Johansson & Vallbo, 1979) it is highly plausible that tactile and sensory information derived from the hand

and fingers may influence sensorimotor control at other regions (L. A. Jones, 1994). Furthermore, by using a hand-grip attachment, force production is not isolated to the GHJ and there will be contributions from the wrist flexor and extensors. Grip strength has also been shown to correlate with isokinetic strength at the shoulder (Mandalidis & O'Brien, 2010), so gripping an attachment may have the potential to influence shoulder strength measurements. Therefore, using an attachment that enables shoulder torque to be translated through the wrist would mitigate for cutaneous sensory influence from the hand, and better reflect influence from local shoulder sensory afferents.

The interface between participant and dynamometer is important, as standard dynamometer hand-grip attachments may introduce confounding tactile feedback from the densely innervated hand as well as recruitment of wrist musculature. Therefore using a wrist attachment may better isolate shoulder contributions and minimise cutaneous sensory influences and wrist musculature involvement.

3.2.7 Visual gain

Visual gain refers to the degree of visual feedback available to participants during torque matching tasks. This can be both in terms of temporal (e.g. continuous or intermittent) and spatial (e.g. resolution) variables. Higher gain relates to greater resolution and therefore more spatial information, and vice versa for lower visual gain. Torque time curves presented for visual feedback, typically display torque on the y-axis and time on the x-axis. How the y-axis is demarked therefore affects the resolution of the resulting force time curve. Previous research has explored this dilemma, with variable findings.

Depending on how 'low' and 'high' visual gain are defined, torque steadiness has been demonstrated to be improved (Kuznetsov & Riley, 2010) or decreased (Kim et al., 2018) with higher gain, or dependent on the torque control task being used (Hong & Newell, 2008). In general, research exploring spatial gain (i.e. resolution of

how torque is represented on the screen) find an inverse U-shaped relationship between visual gain and torque control outcome, with increasing gain leading to steadier torque production, but further increases lead to decreased steadiness (Baweja et al., 2009; Sosnoff & Newell, 2006).

Other research has not demonstrated a significant effect of visual gain on torque steadiness (Baweja et al., 2009, 2011) or accuracy (Hong et al., 2008). The reported role of visual gain on torque control measures therefore remains varied most likely due to methodological differences, but visual gain should be standardised across tasks and participants.

Pilot testing from our lab (n=8) compared three visual gain conditions: high (y-axis scaled so the target torque appeared midway on the axis), medium (y-axis ranging from zero to twice the target torque), and low (y-axis fixed at 0–50 Nm). As no significant effect on torque control was observed, we adopted the high visual gain condition to standardise target presentation at the screen midpoint across all participants and conditions.

3.2.8 Learning Effect

Previous research (Hortobágyi et al., 2001) has demonstrated a learning effect with isometric and isokinetic torque matching trials at the quadriceps. Conversely, at the shoulder, no learning effect was demonstrated across trials and two testing sessions for torque matching of shoulder internal and external rotation (Dover & Powers, 2003). More recently, Magni et al. (2021) found varied results when investigating hand and pinch grip torque control in people with hand OA; grip torque RMS showed a trial number effect, but pinch RMS did not, and neither grip nor pinch torque SD changed significantly over five trials in their healthy cohort. More recently, McNaughton et al. (2022) reviewed sensory attenuation with two finger torque matching tasks finding that performance was stable across trials with no observable

learning trend once the task is underway, which suggests that a smaller number of trials per condition can yield reliable estimates.

Finally, the number of trials used in torque control studies at the shoulder varies, but a common approach is to have participants perform 3-5 trials of a matching task for each target torque level. Therefore, to mitigate learning and order effects as well as minimising participant burden, the number of trials for the static matching task was limited to 5 trials per condition, with task familiarisation during the data collection warm-up.

Previous studies using sinusoidal tracking tasks have had participants perform 3-4 trials (Knol et al., 2019; S. H. Ward et al., 2019). However, given the novel nature of this task at the shoulder ten trials were chosen as pilot study work (n=6) demonstrated a learning effect, with maximum torque matching accuracy reached at six repetitions. To account for this learning effect, 10 trials for the tracking task were used for each condition with data from the final five trials only used in the subsequent data analysis.

3.2.9 Dual Tasking

This section provides key methodological considerations for selecting and implementing a cognitive task in a dual task paradigm include task complexity, choice of cognitive task, presentation parameters, and measurement approach.

Task complexity

Dual task interference - the effect on single task performance, whilst concurrently performing two tasks - is in part dependent on task complexity. Many means of attributing levels of complexity to a task have been described, but recently a dual task taxonomy was proposed by McIsaac et al. (2015) that characterises component tasks by complexity and novelty. Complexity of a task is dependent upon the number of components within a task, how much attentional demand they each require, and

environmental challenges. Novelty is based on an individual's previous task experience and learning effect. Varying the interaction of complexity and novelty can make a task more or less challenging (McIsaac et al., 2015; Plummer & Eskes, 2015), allowing appropriate levels of challenge for both clinical and research applications.

For example, Zijdewind et al. (2006) demonstrated that a higher-intensity (60% MVC) motor task had a greater effect on an auditory reaction task compared to a lower-intensity (30% MVC) torque-matching task. Their findings suggested that as central demand for motor recruitment increases, attentional resources available for concurrent cognitive tasks diminish, leading to reduced cognitive task performance. This mechanism implies that when individuals engage in a more demanding motor task, such as torque tracking, the heightened demand on central attentional processes contributes to cognitive performance errors. Similarly, magnitude of motor performance changes has been demonstrated with perceived complexity of a dual cognitive task. For example, Patel et al. (2014) found that a Stroop task resulted in greater detrimental changes in preferred gait speed than simpler visuomotor reaction, word list generation and serial subtraction tasks.

These findings have been proposed to be due an 'overload' of motor planning and visual feedback resources (Grooms et al., 2015) and dual tasking is known as one method of overloading the central processes involved in resource allocation (Pashler, 1994). Manipulating component task complexity may allow researchers to investigate dual task effect of motor task performance as a function of cognitive task complexity and vice versa. However, the effect of complexity of visual cognitive tasks on motor performance has yet to be fully explored and has been highlighted as an area for future research in a recent systematic review (Ness et al., 2020).

Task complexity should be carefully manipulated, as higher-intensity or more complex motor tasks (e.g., 60% vs 30% MVC) increasingly tax attentional resources and reduce concurrent cognitive performance, with this effect also occurring reciprocally when cognitive task complexity increases.

Choice of cognitive task

Within the context of which cognitive task to pair with a motor task, studies have utilised a wide variety of tasks, with differing rationales based on the construct of interest including working memory, visual processing, auditory processing, and choice reaction tasks. Since the inception of the original colour-word Stroop test (Stroop, 1935), the Stroop effect has been observed with differing visual, auditory, and spatial Stroop-like tasks (Cannon, 1998; MacLeod, 1991; Viviani et al., 2023). A Stroop task is an attractive choice for the cognitive component of a motor-cognitive dual task for multiple reasons. First, the Stroop effect is well documented and Stroop tasks are considered reliable measures (Hedge et al., 2018; Schuch et al., 2022; Siegrist, 1997). Whilst reported reliability data for Stroop (and neurocognitive tasks in general) is scarce (Hedge et al., 2018), recent research (Paap et al., 2020) has demonstrated good split-half reliability (Spearman-Brown = .81) for spatial Stroop tasks. This was supported with reported split-half scores for spatial Stroop task response time and accuracy scores of 0.77 and 0.79 respectively (Capizzi et al., 2017). This demonstrates good internal consistency, producing consistent results within a single administration and supporting the reliability for detecting individual differences. Second, Stroop tasks provide an appropriate cognitive challenge for dual-task paradigms, requiring higher executive processes such as working memory and decision-making when resolving conflicting congruent or incongruent (Kane & Engle, 2003; Patel et al., 2014).

Third, they are less likely to be influenced by an individual's numeracy, literacy, or educational status. Furthermore, the response to Stroop tasks is easy to measure

and quantify (MacLeod, 1992), with response accuracy (i.e. percentage of correct responses) and reaction time (typically ms or secs) providing useful data on task performance, especially when studying changes in performance under dual-task conditions. Importantly, experimental effects of Stroop tasks are well established and easily replicable, with low between-subject variability (Hedge et al., 2018; Schuch et al., 2022).

Specifically, a word-direction Stroop task provides several advantages for motor-cognitive dual-task research. This spatial Stroop variant provides a cognitive challenge that is arguably more ecologically valid and less reliant on participants' literacy or numeracy than traditional colour-word variants. As spatial Stroop tasks require visual sensory processing, they create greater structural interference (interference from tasks competing for the same processing pathways) when paired with a motor task that also requires visual feedback. This has previously been demonstrated, with a visual Stroop task resulting in poorer performance of an obstacle gait task than an auditory task, due to the greater structural interference from the visual compared with auditory tasks (Worden et al., 2016).

The word-direction task also incorporates a choice-reaction component that requires higher order executive function compared to a simple visuomotor reaction task (e.g., reacting to a light flashing). Using foot pedals for the reaction part of this choice-reaction task allows for greater real-world representation, as during tasks such as throwing or tackling, individuals need to plant their foot as they perform the action with their upper limb. This makes the word-direction Stroop task advantageous over other simpler tasks or those that require numeracy or literacy for participants to be assessed. From a methodological perspective, using directional arrows and corresponding direction words ensures that there is interference, maintaining the core Stroop effect. Stimulus-response overlap is also maintained as participants are required to respond to the directional stimulus by depressing the corresponding left

or right foot pedal. These methodological components ensure that this variant maintains the validity of the original colour-word Stroop task (Viviani et al., 2024) whilst simultaneously providing a more ecologically valid challenge for a cognitive-motor dual task paradigm.

Thus, for this study, the spatial word-direction Stroop task was selected for its strong psychometric properties and minimal confounding influence of literacy/numeracy, while the directional variant specifically enhances ecological validity by creating structural interference with visual-motor pathways and incorporating foot-pedal responses that better approximate real-world environments requiring movement decisions and where shoulder injury may occur.

Frequency and duration of cognitive task presentations

The duration and frequency of cognitive task presentations for a dual task paradigm is difficult to specify (Schnittjer et al., 2021), with many studies not reporting on those factors. The interval between stimuli presentations can also affect an individual's ability to react under the dual task condition, with short intervals (faster than 1.5secs) leading to significantly greater errors in task performance (Broglio et al., 2005). This has led to researchers using different interstimulus intervals for example fixed 2-second intervals (Schnittjer et al., 2021) or randomised intervals of 3-6 seconds (Temprado et al., 2015). In addition, the duration of the cognitive task should equal the duration of the motor task to allow assessment of both tasks fully in a dual task paradigm (Broglio et al., 2005). In summary, to minimise influence of error rates, presentation of stimuli needs to be long enough in duration for participant response, have intervals of between 3-6 seconds, and for the stimuli to be presented over the duration of the motor task.

Task prioritisation, and dual task effect

Most studies of dual task effect fail to measure the change in performance of both tasks instead only reco(Plummer et al., 2013, 2016; Plummer & Eskes, 2015)13,

2016; Plummer & Eskes, 2015). By not measuring the change in cognitive task performance the opportunity to study dual-task interference and allocation of attentional resources is lost. Measuring reciprocal changes in task performance is also important for identifying dual task performance over time (Plummer & Eskes, 2015) which may be of clinical relevance when considering whether an individual is improving at dual task performance or simply prioritising one task over another.

The fact that an individual can self-select strategies dependent on the task characteristics is supported by the work of Yogev-Seligmann and colleagues (Yogev-Seligmann et al., 2012) who put forward the model of task prioritisation based on observations of dual tasking during walking. Their model proposes that task prioritisation is based on motor and cognitive factors such as task complexity, as well as factors associated with the individual such as expertise and skill. Higher attention-demanding tasks have been shown to induce earlier signs of task prioritisation.

Healthy individuals demonstrated a decline in performance of a cognitive finger-tapping task when presented with a concurrent stimulus to perform a stepping task indicating a selective shift of attention (Sun & Shea, 2016). When the stepping task involved a choice-reaction, and therefore higher executive function, early anticipatory changes in posture were observed indicating prioritisation of attention to the more complex motor stepping task. Similarly, in a cohort of healthy young individuals, cognitive task performance (reaction time and accuracy) was sacrificed to maintain jump-landing performance indicating a prioritisation strategy to maintain motor performance (Biese et al., 2019).

Hence, performance changes in both tasks should be measured rather than motor performance alone, as this allows proper assessment of dual-task interference, attentional resource allocation, and task prioritisation strategies. It was therefore decided to calculate dual task effects for greater insights into any observed dual task performance differences.

3.3 Methods

3.3.1 Study Design

An observational cross-sectional experimental study design was used to investigate the effect of the addition of a secondary cognitive task (visual Stroop task) on shoulder torque control performance in a population of healthy young adults.

3.3.2 Ethical Approval

Ethical approval was provided by the New Zealand Health and Disability Ethics Committee (HDEC) (reference 21/NTB/98) and Auckland University of Technology Ethics Committee (AUTEC) (reference 21/348).

3.3.3 Sample Size Calculation

Sample size calculations were performed in G*Power v3.1.9.6 (Faul et al., 2007). There was no existing literature deemed sufficiently similar to the planned study to base our sample size calculation upon. Hence, pilot testing (n=6) was completed before data collection began to establish means and SDs, using the test procedures described in the Sections 3.3.10 and 3.3.11. The participants in the pilot work were representative of the study cohort in age and health status (3M:3F, Age Range 20-29), and no pilot participant was included in the final study sample. The dependent variables of interest were (1) internal rotation steadiness (SD) and accuracy (RMS error) during torque matching (with visual feedback) and (2) accuracy (RMS error) during torque tracking.

For torque matching, the mean \pm SD for steadiness and accuracy were 0.32 \pm 0.14Nm and 0.35 \pm 0.17Nm respectively. For torque tracking, the mean \pm SD for accuracy was 2.37 \pm 0.54Nm. For all sample size calculations, two-tailed tests were used with an α level of 0.05, power of 80% and an estimated correlation between repeated measures of $r=0.7$. Previous studies (Pereira et al., 2015, 2018) investigating elbow flexor torque steadiness under motor-cognitive dual task conditions have demonstrated changes in steadiness (CV) of between 59 and 77% in healthy young

cohorts. As shoulder torque control tasks differ in complexity and attentional demand, to detect a more conservative 25% difference in the variables of interest between single and dual task conditions (matched pairs), sample size calculations yielded $n=20$ for torque matching RMS, $n=17$ for torque matching SD, and $n=7$ for tracking RMS. The largest required sample ($n=20$) was used to determine the recruitment target. To account for a maximum dropout rate of 10%, the recruitment target was set at 22. A 25% change corresponds to an absolute between condition difference of 0.09 for torque matching RMS ($d=0.51$), 0.08 for torque matching SD ($d=0.57$) and 0.59 for tracking RMS ($d=1.10$) Pilot testing in the same cohort ($n=6$) established excellent test-retest reliability for torque matching RMS ICC=0.99, 95%CI [0.92,1.00], SEM=0.02, torque SD ICC=0.95, 95%CI [0.66,1.00], SEM=0.03, and for tracking RMS ICC=0.95, 95%CI [0.87,0.99], SEM=0.12. Using these values, the minimum detectable change for the group differences (MDC_{GROUP}) was calculated as 0.01 for RMS and 0.02 for SD for the torque matching task, and 0.07 for RMS for the torque tracking task ($MDC_{GROUP} = (SEM \times 1.96 \times \sqrt{2}) / \sqrt{n}$, where $n = 20$). Importantly, the target between-condition differences used in the power calculations exceeded their respective MDC_{GROUP} values by factors of 9.0, 4.0, and 8.4 respectively, indicating that the measurement approach utilised possesses sufficient sensitivity to detect the minimum effects for which the study was powered.

3.3.4 Participant Recruitment

Twenty-two healthy volunteers were recruited via recruitment posters placed on university noticeboards and snowball sampling. A cohort of young adults was sought to represent an active population likely to participate in sports/activities with an inherent risk of shoulder injury, and where torque control at the shoulder may be important. Potential participants were screened for inclusion and exclusion criteria via phone conversation by the principal investigator. Those participants who met the inclusion and exclusion criteria were invited to participate via consecutive sampling.

No study participants had previously taken part in pilot testing. All participants provided written informed consent prior to commencement of data collection and were then considered enrolled in the study.

3.3.5 Inclusion & Exclusion Criteria

The following inclusion and exclusion criteria were applied:

Inclusion: Individuals aged 20-35 years, without a history of shoulder injury (criteria for shoulder injury were any shoulder or upper arm symptoms that had necessitated input from a health care professional).

Exclusion: Current or past upper limb or spinal pathology that required management by a health professional, history of a neurological condition, other forms of global joint pathology (e.g. hypermobility syndrome, arthropathies) and non-fluency in the English language.

Prior to data collection, participants were screened for shoulder ROM and the apprehension test (Tzannes & Murrell, 2002). This screening was performed by the principal investigator, a physiotherapist with over 20 years of clinical experience. All participants demonstrated sufficient GHJ ROM for the testing protocol (90° of abduction and 90° external rotation) and none demonstrated significant hypermobility (>180° of total rotation in 90° abduction (Nicholson & Chan, 2018)) or a positive shoulder apprehension test.

3.3.6 Participant Characteristics

A questionnaire created in REDCap (Research electronic data capture (Harris et al., 2009)) was used to collect patient characteristics such as age, height, weight, and ethnicity. Defining sports participation and expertise varies considerably in the literature, especially across sports (Swann et al., 2015). Therefore, sports participation was defined pragmatically (social=recreational e.g. friends and family; competitive = take part in organised league or events; elite = representative (e.g.

region/national). No participants participated in competitive or elite level overhead sports defined as 'a sport in which an athlete, with the forearm/hand lifted above the head, repetitively propels a ball or shuttle against an opponent or a teammate' (Asker et al., 2018).

3.3.7 Experimental Set-up

The shoulder to be tested (dominant or non-dominant) was randomly selected, and counter-balanced for each participant using a computer-generated randomisation schedule. Participants were then positioned in an isokinetic dynamometer (Biodex 3, Biodex Medical Systems, Shirley, NY, USA) for all tasks. Once comfortably seated, participants had their selected arm positioned in the attachment of the dynamometer in 90° of glenohumeral elevation in the scapula plane, 80° of glenohumeral external rotation and with their elbow flexed to 90°. Their elbow and humeral shaft were aligned with the axis of rotation of the dynamometer. Straps were applied across the chest and lap to prevent extraneous movement, and the head rest was adjusted so that the participants could comfortably maintain their head against the rest when instructed (see Figure 6). Participants feet were placed on a block either side of the foot pedals used for indicating responses to the visual Stroop task (VST).

A custom-made stainless-steel attachment was designed and built by a local engineering company (The Steelworks Engineering Co NZ Ltd). It was fitted onto the Biodex shoulder attachment without altering the original connection to the dynamometer. This attachment negated the opportunity of generating torque at the hand or receiving tactile sensory feedback across the hand.

3.3.8 Warm-up and Shoulder Peak Torque

In order to optimise maximum torque production and reduce risk of injury, a warm-up was included to familiarise the participants to the task specific demands of maximum isometric testing (Brown & Weir, 2001). Participants followed a standardised warm-

up of 10 shoulder circumductions in forwards and backwards directions followed by ten wall press-ups. Immediately prior to the MVC collection, participants were instructed to produce 25%, 50% and 75% effort isometric contractions on the Biodex with visual feedback provided via a PC monitor set at 1.5m from the participant. Two repetitions of five seconds duration were performed at each effort level. The warm-up period also allowed for familiarisation with the equipment and participants' confidence with the tasks.

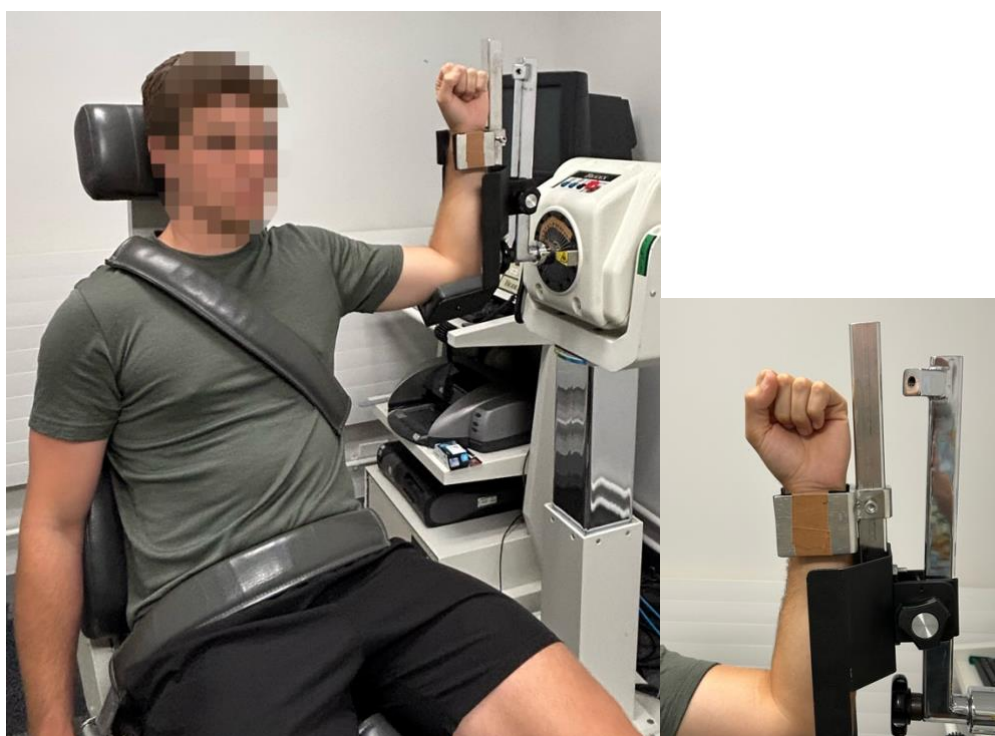


Figure 6. Participant Set Up & Custom Wrist Attachment (Close Up)

Maximum voluntary contraction (MVC) for isometric shoulder internal and external rotation was recorded as the highest torque achieved across the three trials (Dover & Powers, 2003). The order of direction testing was randomised for each participant. Each MVC was separated by one-minute rest intervals, and two minutes rest was applied between internal and external rotation testing. Verbal encouragement was given to ensure a true maximum was reached (McNair, Depledge, et al., 1996).

Additionally visual feedback of their torque production was provided to the participants on a PC monitor.

3.3.9 Order of Testing

Following warm-up and MVC testing, participants were required to perform a series of isometric torque matching (TMT), isometric torque tracking (TTT), and visual Stroop tasks (VST) under single-task conditions in a randomised and counter-balanced order. Randomisation and counterbalancing were performed in Excel (Microsoft® Excel for Mac v16.84). A single familiarisation trial was allowed for each task. Following the performance of all tasks individually, participants performed the TMT and TTT tasks simultaneously with the VST under dual-task conditions, following the same order as performed for the torque control tasks under single condition (see Figure 7).

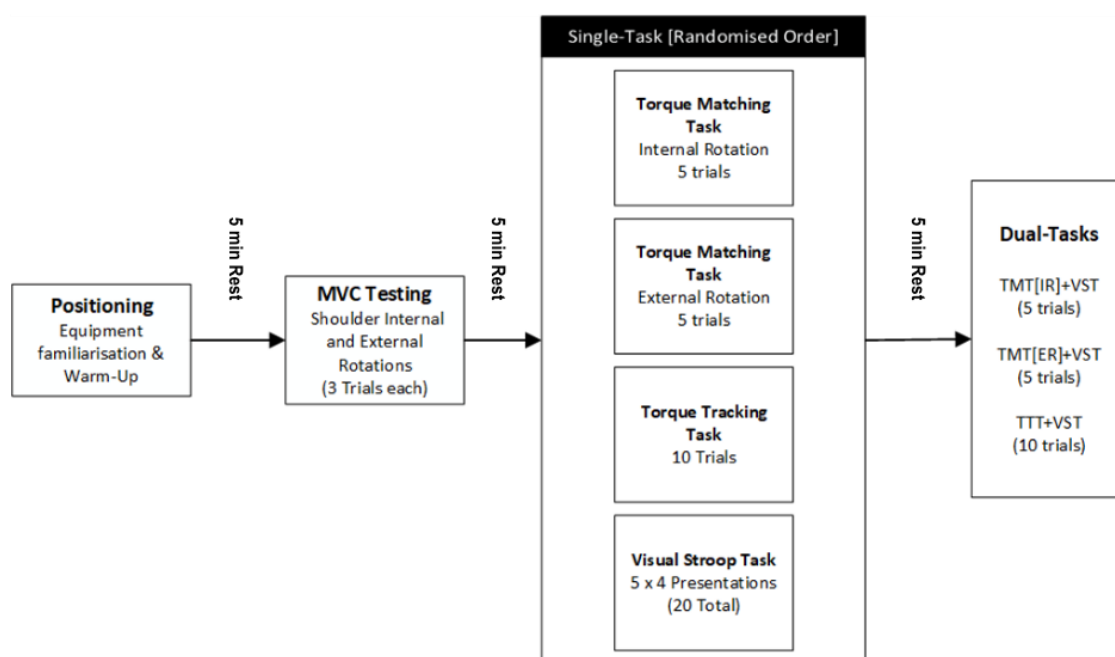


Figure 7. Data collection process

3.3.10 Isometric Torque Matching Task

For all tasks, real time torque data were displayed on the PC monitor via a custom computer program made in DASyLab (Data Acquisition System Laboratory, DasyTec USA, Inc., Amherst, NH). Participants were required to wear glasses or

contact lenses if normally worn for everyday vision at such distance. Participants' target torque of 35% MVC was displayed as a horizontal line centred on the screen by setting the y-axis accordingly (see Figure 8). In previous pilot work for other studies undertaken in our lab group, a comparison of bar graph displays and lines showed that in the former participants had greater difficulty understanding the task and also performing it. More outlier like responses within trials and difficulty learning the task required was apparent.

An indicator light was used to signal to the participant to initiate their force production. When the indicator light was switched on, they were to generate their torque up to the target torque line as quickly as possible, and when at the line, to hold their torque line as close to target and as steady as possible until instructed to relax. Five trials separated by a minute were performed for internal and external rotation, in a randomised order (Sacco et al., 2014). In each trial, the participant was required to hold their torque at the target force line for a minimum of 20 seconds. This allowed for the matching task to be equal in duration as the visual Stroop task, and for sufficient duration and inter-presentation interval of each presentation during the dual task condition.

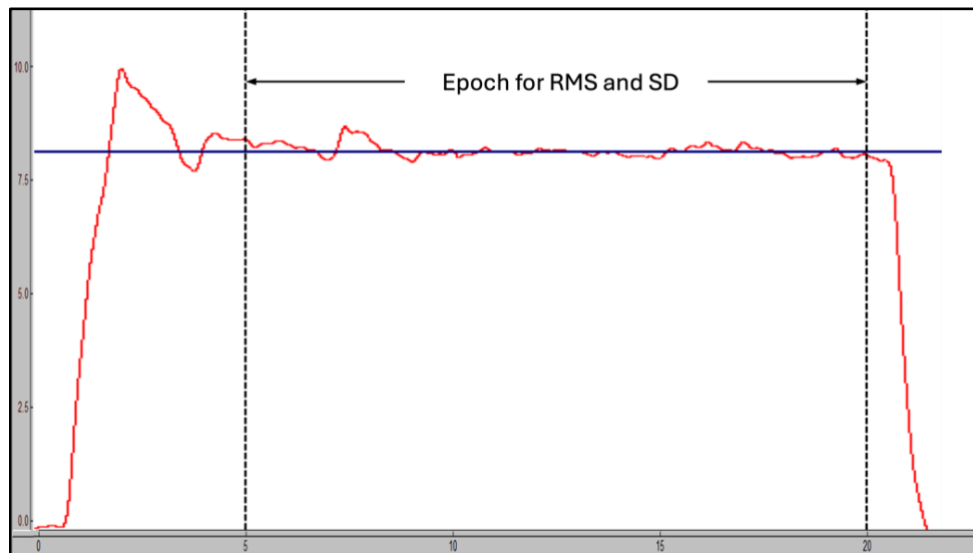


Figure 8. Example of a 35% MVC torque matching task incl. window for torque control variables calculation (*x-axis represents time [secs]; y-axis represents torque [Nm]; SD=standard deviation, RMS=root mean square; Solid horizontal line represents the 35% MVC target*)

3.3.11 Isometric Torque Tracking Task

For the torque tracking task, participants were required to produce both internal and external rotation isometric contractions of varying relative torque values to follow a standardised sinusoidal pattern, ranging between 10 and 60% MVC for 15 seconds. The target torque line was generated using the custom software described in Section 3.3.10 and presented on the screen as a sinusoidal target trace. The frequency of the waveform was 0.4Hz (6 cycles over a 15s epoch). This frequency and target torque levels were based on piloting conducted in the lab. Pilot work demonstrated that the frequency of the sinusoid wave allowed adequate time for participants to transition between internal and external rotator muscle activity and to control activation when nearing torque peaks. Faster frequencies often resulted in an inability to reach the peak torques or overshooting and subsequent responses being excessive and indicative of trying to catch up with the target signal.

Participants were instructed to hold their torque line at a position of zero torque just prior to the start of the sinusoidal pattern to standardise the starting position of their torque. They were then instructed to follow the sinusoidal pattern as closely as possible by alternating between isometric internal and external rotator muscle

activation (see Figure 9). Ten trials were performed separated by one minute between trials. Ten trials were chosen as pilot study work (n=6) demonstrated a learning effect, with maximum torque matching accuracy reached at six repetitions. To account for this learning effect data from the final five trials only was used in the subsequent data analysis.

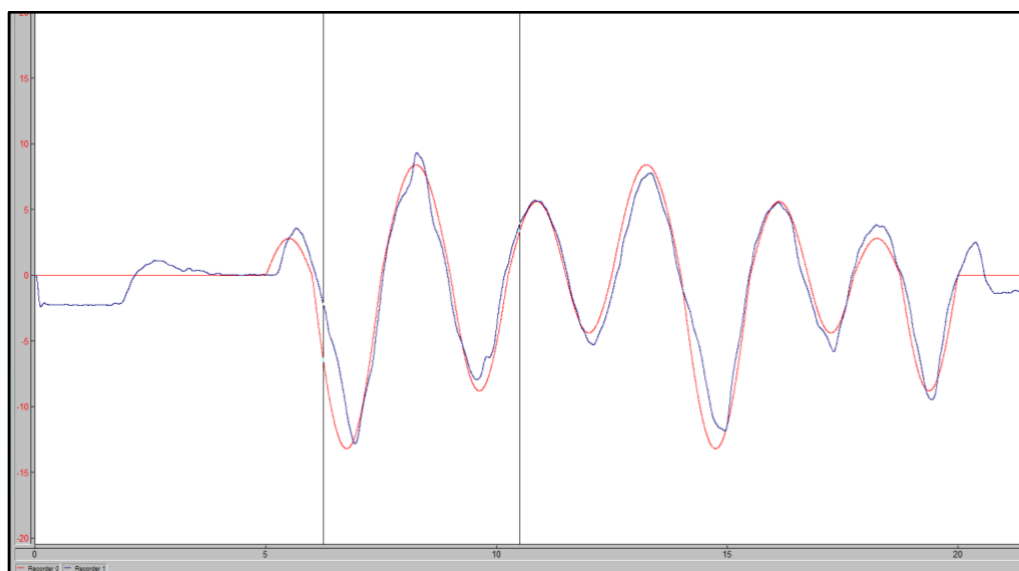


Figure 9. Example of a participant torque tracking task trial (*x-axis represents time [secs]; y-axis represents torque [Nm]; the red line is the target torque line; the blue line is the participant's generated torque*)

3.3.12 Visual Stroop Task

Participants were seated in the same set-up as for the force matching tasks. They were presented with a congruent and non-congruent word-direction spatial Stroop task (Cannon, 1998; Shor et al., 1972) via the same computer monitor and within the same custom computer program described in section 3.3.10. In a congruent presentation the direction word was bookended by arrows pointing in the same direction e.g. “< **LEFT** <”. Non-congruent presentations had the arrows pointing in the opposite direction e.g. “> **LEFT** >”. Participants were instructed to respond to the direction of the arrow as quickly and as accurately as possible by depressing the corresponding foot-pedal; that is when the screen presented < **RIGHT** <, the

participant should press the LEFT foot pedal. They had a single familiarisation trial followed by five recorded trials. Each trial consisted of four pre-generated randomly ordered congruent and non-congruent word-direction presentations. An equal number of congruent and non-congruent presentations were used, with each presentation lasting two seconds, and the inter-presentation interval lasting three seconds.

3.3.13 Cognitive-Motor Dual-Task

For the dual task condition, participants were required to perform the torque tasks simultaneously with the visual Stroop task. They were provided with the same instructions for the tasks; however, they were given no indication or suggestion as to which task should be prioritised.

3.3.14 Data Sampling

The analogue torque signal from the dynamometer was transmitted to an analogue/digital data acquisition unit (instruNet Model 100B, GW Instruments Inc., Charleston, MA, USA), sampled at 1000Hz and displayed on a PC via a custom-built software program DASyLab (Data Acquisition System Laboratory, DasyTec USA, Inc., Amherst, NH). The signal was filtered using a 20Hz low-pass fourth order Butterworth filter. This allowed for filtering of undesirable signal noise but also ensured the signal was not overly smoothed (Thompson, 2019).

At the same sampling rate, analogue signals (3-volt pulse) associated with the start of the trial and from the foot pedals were also passed through the data acquisition unit on separate channels.

3.3.15 Data Processing

Data was inspected visually and saved for further analyses. All data were processed, and the relevant variables of interest recorded and entered into a spreadsheet

(Microsoft® Excel for Mac v16.84). These data were then screened for any inputting errors or omissions.

3.3.16 Dependent Variables

A summary of the dependent variables of interest can be found in Table 4. For the torque matching task, torque steadiness was measured as the standard deviation (Santos et al., 2016) of the participant torque around the mean torque value over the central fifteen seconds. The 15-second epoch aligned with the period just prior to the first VST presentation until just after the duration of the final VST presentation during the dual task condition. The epoch was therefore kept the same for the single task torque matching for fair comparison. Torque matching accuracy was measured as the root mean square (RMS) error (Trousset et al., 2018) over the same epoch. For the torque tracking task, RMS error was calculated across the whole 15-second duration of the final five trials and aligned with the duration of the VST presentations during the dual task.

Table 4. Study variables and method of measurement

Variable	Unit	Measurement
Torque Steadiness (SD)	Nm	Standard deviation of the torque signal around the mean torque value over the central 15 secs of the torque signal (the higher the value the less steady the torque)
Root Mean Squared (RMS) Error	Nm	A measure of the average magnitude of the error between the target torque and the participant's generated torque, taken from the central 15 secs of the torque signal
VST Accuracy	%	The proportion of the participant's responses that are correct.
VST Response Time	Secs	Time taken for participant to identify correct responses (Δ from the VST presentation to the participant's depression of foot pedal)

Note: VST = Visual Stroop Task

The VST correct responses were determined by referencing participant responses against the predetermined VST presentations for each trial, giving a percentage measure of accuracy. Reaction time for the correct responses was also recorded.

3.3.17 Dual Task Effect

Dual-task effect is the relative change in task performance related to dual-tasking, and is calculated as follows:

$$DTE (\%) = \frac{(Dual\ Task\ parameter - Single\ Task\ parameter)}{Single\ Task\ parameter} \times 100$$

For negative changes in performance, the value can be inverted to give a negative value to represent decrease in performance.

The addition of dual task effect calculations (V. E. Kelly et al., 2010) aids understanding in task prioritisation strategies by quantifying the magnitude and direction of change in performance of both tasks (Plummer & Eskes, 2015). Thus, DTE can be observed from the following perspectives:

- 1) Decline in performance of both tasks (*Mutual interference*)

- 2) Motor task improvement with cognitive task decline (*Motor-priority trade-off*)
- 3) Motor task improvement with cognitive task improvement (*Mutual facilitation*)
- 4) Motor task decline with cognitive task improvement (*Cognitive-priority trade-off*)

3.3.18 Statistical Analyses

Descriptive analyses were performed, and the normality of the distribution of the data was tested using Shapiro-Wilk tests. For the internal rotation torque matching task, visual Stroop task reaction times for single task and dual task were normally distributed, so paired samples t-test were used for comparison between single and dual task performance. All other variables of interest were non-normally distributed. Therefore, Wilcoxon signed-rank tests were used to compare means across the task condition (single vs dual). An alpha level of $p < 0.05$ was used for all statistical analyses. For non-parametric tests, the r effect size was calculated via the following formula: $r = \frac{z}{\sqrt{N}}$ (where r =effect size, z =z statistic, and N =number of observations), with effect sizes interpreted as: small=0.10, medium=0.30, large=0.50 (Rosenthal, 1994). For paired samples t-tests, effect size was calculated using Cohen's d for paired samples, with the effect sizes interpreted as: small=0.20, medium=0.50, large=0.80 (Cohen, 2013).

Due to multiple comparisons, a family-wise error rate is introduced, that is the probability of a Type I error (i.e. rejecting the null hypothesis when it is true). In accordance with previous literature, a percentage error rate (PE) was calculated which reflects the proportion of statistically significant results that are likely to be Type I errors (Ottenbacher, 1991). The percentage error rate was calculated using the formula: $PE = 100 \times c\alpha/m$ (where c is the number of comparisons, α is the α set for the individual comparisons, and m is the number of tests equal to or less than the

α rate). This was a preferable method to using the Bonferroni adjustment for multiple tests, as this has previously been described as increasing potential Type II errors, and describing what significance tests have been reported as being preferable (Perneger, 1998).

3.4 Results

A total of 22 potential participants were recruited for the study. One participant was subsequently excluded due to ongoing effects of a concussion injury. Another participant failed to reply to communications to schedule data collection. The remaining 20 participants provided written and informed consent and completed data collection. Participant characteristics are displayed below (Table 5). No adverse effects of the testing procedures were reported.

A summary of all the findings is displayed below (Table 6). In the following sections, the main findings are presented by task: torque matching task, torque tracking task, and visual Stroop task.

Table 5. Baseline characteristics across all participants, n=20 (data presented as mean \pm one standard deviation, or as number/proportion as a percentage)

Gender	10(50%) Female	Sports	
	9(45%) Male	N/A	4(20%)
	1(5%) Gender Diverse	Climbing	2(10%)
Age (yrs)	23.4 \pm 3.32	Football	2(10%)
Height (cm)	169.1 \pm 10.33	Running	2(10%)
Weight (kg)	67.85 \pm 12.81	Badminton	1(5%)
BMI (kg/m²)	23.54 \pm 2.46	Cricket	1(5%)
Ethnicity		Golf	1(5%)
NZ European/Pākehā	10(50%)	Gym	1(5%)
Other European	3(15%)	Hockey	1(5%)
African	2(10%)	Horse Riding	1(5%)
Southeast Asian	4(20%)	Netball	1(5%)
Indian	1(5%)	Tennis	1(5%)
Limb Dominance		Weightlifting	1(5%)
Right	18(90%)	Level	
Left	2(10%)	Social	11(55%)
Limb Tested		Competitive	5(25%)
Dominant	10(50%)	N/A	4(20%)
Non-dominant	10(50%)		

3.4.1 Torque Matching Task

For internal rotation, torque was significantly steadier (i.e. SD was lower) for single task compared with dual task conditions ($z=-3.248$, $p=.001$, $r=-0.73$).

Similarly, for external rotation, torque was significantly steadier for single task compared with dual task conditions ($z=-2.165$, $p=.03$, $r=-0.48$).

Table 6. Torque control and visual Stroop task variables under single and dual task conditions

Task	Single	Dual	p-Values	Effect Size (r)	Effect Size (d)
TMT (IR)					
SD	0.31(0.21-0.46)	0.47(0.33-0.80)*	0.001	-0.73	
RMS	0.34(0.27-0.47)	0.54(0.39-0.97)*	<0.001	-0.83	
TMT (ER)					
SD	0.28(0.21-0.43)	0.45(0.32-0.55)*	0.03	-0.48	
RMS	0.39(0.23-0.49)	0.50(0.36-0.63)	0.09	-0.38	
TTT					
Total RMS	2.66(2.36-5.66)	3.27(2.78-5.70)*	0.008	-0.59	
VST					
Accuracy	100(95.0-100)	IR TMT	100(96.3-100)	0.43	-0.17
		ER TMT	100(95.0-100)	0.74	-0.07
		TTT	50.0(45.0-50.0)*	<0.001	-0.89
Reaction Time	0.79 +/- 0.15	IR TMT	0.85 +/- 0.18	0.11	-0.37
		ER TMT	0.75(0.71-0.91)	0.23	-0.27
		TTT	0.83(0.77-0.88)*	0.02	-0.53

Note: Values shown are median and interquartile ranges or means \pm SD. TMT = torque matching task, TTT = torque tracking task, VST = visual Stroop task, SD = standard deviation, RMS = root mean square, IR = internal rotation, ER = external rotation * significant difference between tasks $p < .05$.

For internal rotation torque matching, accuracy was significantly impaired under dual compared with single task condition ($z=-3.73$, $p<.001$, $r=-0.83$). For external rotation, torque matching accuracy for single task compared with dual task conditions was not significantly different ($z=-1.68$, $p=.09$).

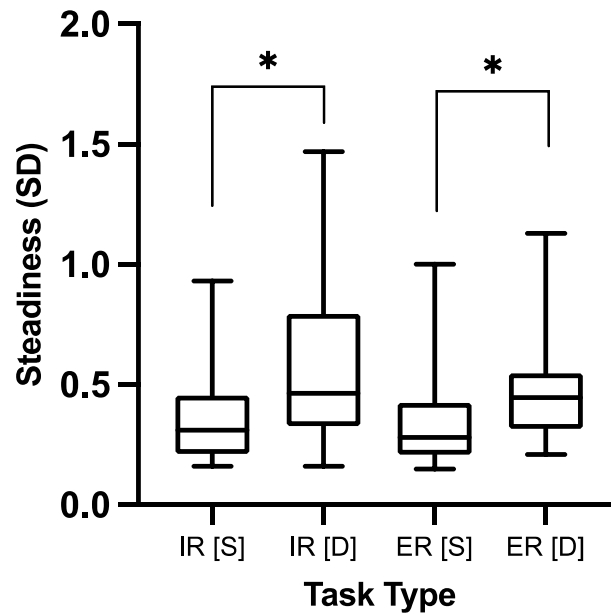


Figure 10. A box and whisker plot showing torque steadiness (SD) for shoulder internal and external rotation torque during isometric torque matching tasks at 35% MVC, when performed as a single task and with the addition of a visual Stroop task (*IR=internal rotation; ER=external rotation; S=single task; D=Dual task*). Note: lower values represent greater torque steadiness.

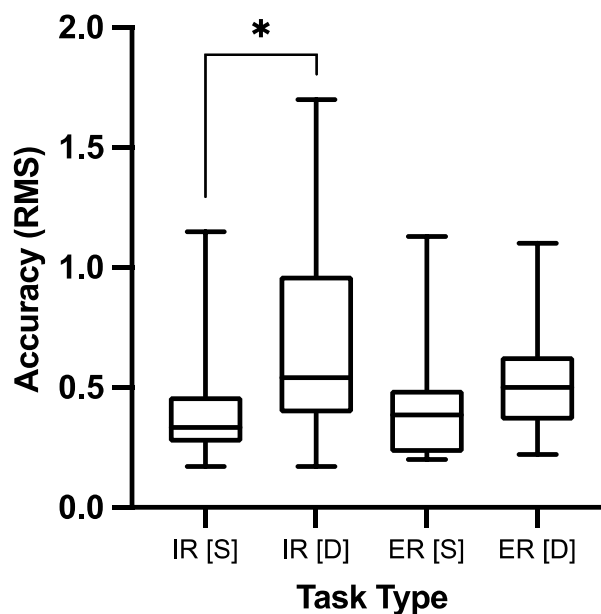


Figure 11. A box and whisker plot showing torque accuracy (RMS) for shoulder internal and external rotation torque during isometric torque matching tasks at 35% MVC, when performed as a single task and with the addition of a visual Stroop task (*IR=internal rotation; ER=external rotation; S=single task; D=dual task*). Note: lower RMS value represents greater accuracy.

3.4.2 Torque Tracking Task

For the torque tracking task, overall torque matching accuracy was significantly lower during dual task compared to single task performance ($z=-2.65$, $p=.008$, $r=-0.59$).

3.4.3 Visual Stroop Task

There were no significant differences between VST accuracy between single task or dual task performance for internal ($z=-0.782$, $p=.43$) or external rotation ($z=-0.33$, $p=.74$) TMT. Similarly, no significant differences for VST reaction time were observed for either internal or external rotation ($z=-1.672$, $p=.11$; $z=-1.195$, $p=.23$ respectively).

When paired with the TTT, VST accuracy was significantly lower during the dual task compared to single task condition ($z=-3.98$, $p<.001$, $r=-0.89$). Reaction times were also significantly slower under dual task with the TTT, compared with single task condition ($z=2.35$, $p=.02$, $r=-0.53$).

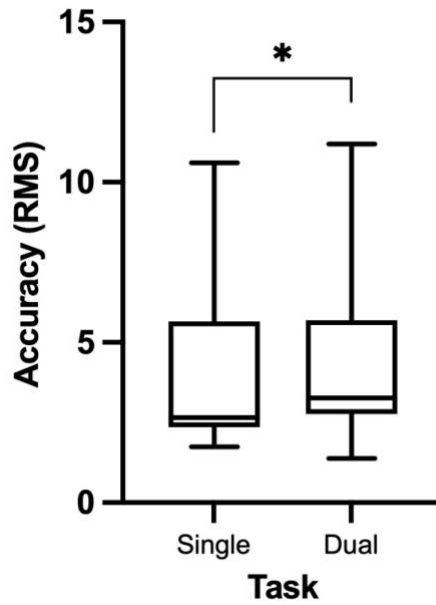


Figure 12. A box and whisker plot showing torque accuracy (RMS) during an isometric torque tracking task using the shoulder internal and external rotators when performed as a single task and with a combined visual Stroop task. *Note: lower RMS value represents greater accuracy.*

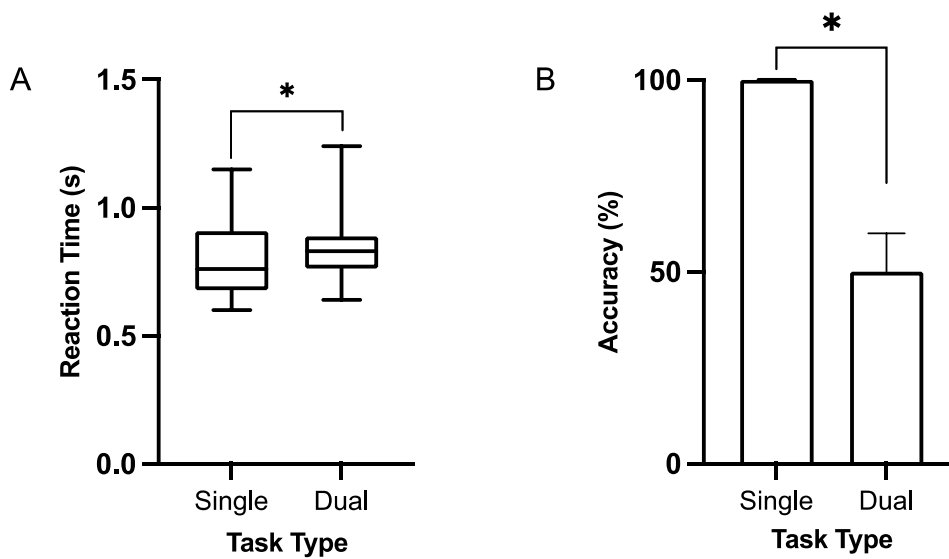


Figure 13. Visual Stroop task performance as a single task and with the addition of the torque tracking task. Panel A (left) a box and whisker plot showing participant response reaction time; Panel B (right) a bar chart showing participant response accuracy rate.

3.4.4 Dual Task Effect

For the torque matching tasks, changes in torque accuracy (-64% for IR and -41% for ER) and steadiness (-73% for IR and -39% for ER) were far greater than those for

the VST accuracy (2% IR dual task, 2% ER dual task) and reaction times (-8%, -2%). This reflects a cognitive-priority trade-off i.e. motor task performance was sacrificed for the cognitive task performance.

In contrast, for the torque tracking task, changes in torque accuracy (-23% RMS) were accompanied by changes in VST accuracy (-49%). Under these conditions, mutual interference was demonstrated between torque tracking and VST performance (decreased accuracy), albeit that greater dual task interference was observed for Stroop task.

3.4.5 Family-wise Error

Eleven comparisons were made across the study, with the α for each comparison set at 0.05. Of the 11 statistical comparisons, five were found to be significant. The percentage error rate was therefore 11%.

3.5 Discussion

We hypothesised that during dual-task conditions torque steadiness and accuracy, as well as cognitive performance, would be impaired compared to single-task conditions. We anticipated that these impairments would be more pronounced when the torque control task was more complex (torque tracking versus simple torque matching). Our results largely supported our hypotheses demonstrating that the addition of a visual cognitive dual task resulted in decreases in measures of torque control. For the internal and external rotation torque matching task, torque steadiness was significantly decreased. Internal rotation matching accuracy was also decreased under dual task conditions, but external rotation accuracy was not significantly different. For the torque tracking task, total RMS error was significantly greater (i.e. less accurate) with the addition of the visual Stroop task.

When examining the visual Stroop task results for the isometric torque matching task, no significant differences were observed between single and dual tasks. This

indicates a dual task effect with a cognitive task trade-off. In contrast, visual Stroop task accuracy and reaction times were significantly lower and slower respectively, under dual task condition with the torque tracking task compared to single task performance. These results demonstrate a dual task effect of mutual interference.

This study is the first to explore the effects of dual task interference on torque control at the shoulder. However, the findings are comparable to other studies that have employed a motor-cognitive dual task paradigm in the upper limb. In a population of healthy university students, Temprado et al. (2015) demonstrated that torque steadiness of index finger abduction at a 50% MVC target torque was impaired with the introduction of an auditory reaction task. Similarly, isometric torque control of the elbow flexors in young healthy adult groups also display decreases in steadiness with concurrent numeracy tasks (H. M. Pereira et al., 2015, 2018, 2019).

During dual task performance, structural interference is proposed to occur when both tasks require central processing via the same neuroanatomical structure and/or pathway (Pashler, 1994). The result is a change of output of one task whilst the competing task is processed (Hiraga et al., 2009; Temprado et al., 2001). Cross-modal sensory integration has been demonstrated between sensorimotor centres and visual cognition regions e.g. the (Chaput, Onate, et al., 2022; Livett et al., 2022; Wasaka & Kakigi, 2019) (Chaput, Onate, et al., 2022; Livett et al., 2022; Wasaka & Kakigi, 2019). Structural interference is therefore a likely mechanism during dual tasking with motor and visuo-cognitive tasks, explaining the general changes observed in torque control with the addition of the visual Stroop task. However, this mechanism alone doesn't fully explain the differences in dual task effect seen between the torque matching and torque tracking tasks. The observed decreases in torque accuracy likely result from both central interference, arising from competing demands on shared sensorimotor and cognitive processing regions, and structural interference from competing demands on visual processing pathways when both

tasks require visual input. The greater interference effects observed during the more complex tracking task suggest that as motor task demands increase, the competition for these shared neural resources intensifies, leading to more pronounced performance decrements.

Another theory of the mechanisms behind dual tasking relates to allocation of attentional resources (Pashler, 1994), with a premise that there is a finite resource of attention that can be divided between competing stimuli (Oberauer, 2019; Pashler, 1989). Selective attention refers to the ability to attend to relevant stimuli and disregard irrelevant stimuli (Desimone & Duncan, 1995; Moore & Zirnsak, 2017). Attention can be dependent on the salience of the stimuli (so called bottom-up attention) or internal behavioural goals and motivational state (top-down attention) (Moore & Zirnsak, 2017). It is plausible that participants in this study diverted their attention towards the task they perceived as more challenging, depending on the task combination.

This strategy is supported by the findings of Ager et al. (2024) who recently showed a dual task effect of a decrease in shoulder angle reproduction accuracy during functional reaching when paired with a serial subtraction task. In contrast, when paired with the same cognitive task, participants demonstrated an *improvement* in accuracy with a shoulder rotation angle matching task in a Biodex system. The authors suggested that this strategy was due to an individual's prioritisation of task accuracy based on the perceived level of challenge of the task. A similar task prioritisation effect might explain the differences in dual task effect between the relatively simpler isometric torque matching task and the more challenging torque tracking task in the present study. Research (Sun & Shea, 2016) demonstrated that among healthy individuals, cognitive tapping task performance significantly decreased when a concurrent motor stepping task was introduced, indicating attention was shifted to the stepping task. Furthermore, with a choice-reaction

stepping task, involving higher executive function, early postural shifts were observed, again indicating a prioritisation of attention to the motor stepping task. Future research should investigate how participants perceive task complexity during shoulder torque control tasks, and whether these perceptions correlate with prioritisation strategies and dual task performance outcomes.

Whilst the addition of the visual Stroop task affected torque control performance, visual Stroop task performance was also influenced by the mode of the torque control task. Previously Zijdwind et al. (2006) showed a greater effect on an auditory reaction task during a higher intensity (60% MVC) target level compared to 30% MVC torque matching task. The authors suggested that, when there is greater central demand for motor recruitment, attentional resources for concurrent tasks are reduced, hence the drop in cognitive task performance. One implication of this mechanism is that, when faced with a more demanding motor task such as torque tracking, greater demand is placed on central attentional processes resulting in cognitive performance errors.

The effect of dual tasking on corticospinal excitability has been investigated to understand mechanisms behind observed changes in motor performance. A systematic review and meta-analysis (Corp et al., 2014) reported that compared to single task, dual tasking resulted in changes in corticospinal excitability, but the direction of these changes varied across studies, most likely due to methodological differences, particularly concerning cognitive task difficulty. A transcranial magnetic stimulation (TMS) study of the effect of a cognitive-motor dual task in a healthy cohort demonstrated changes in both motor evoked potentials (MEPs) and the cortical silent period (CSP) (Holste et al., 2016). Increases in MEP during dual tasking, indicating greater overall corticospinal excitability was observed alongside increases in CSP, indicating increased GABA-B mediated motor cortex inhibition. The authors postulated that the increases in MEP were compensatory to the

increase in CSP to maintain motor performance albeit with greater motor output variability demonstrated by an observed decrease in finger abduction torque steadiness.

The regulation and control of muscle force is considered essential for joint stability (Clark et al., 2023). At the shoulder, the rotator cuff has been shown to rely on a feedforward mechanism with early onset of cuff activity demonstrated prior to planned movement (David et al., 2000) and expected perturbations (Day et al., 2012). These findings (David et al., 2000; Day et al., 2012) indicate the important role of sensorimotor mechanisms in shoulder function, and it is therefore plausible that impaired torque control during cognitive dual tasking may increase the risk of shoulder injury, as has been intimated in the lower limb (Gokeler et al., 2021; Wilke & Groneberg, 2022). There is a discernible need for research into both the ability to improve motor-dual task performance with training, and any potential effect this may have on reducing injury risk at the shoulder.

As the first study to investigate a motor-cognitive dual task paradigm at the shoulder, a key strength of the present study was the novel combination of a shoulder submaximal torque control task with a visual Stroop task, contributing to the knowledge base in this field. The clinically relevant testing position (apprehension position) with torque target levels representative of typical rotator cuff activation levels provides ecologically valid insights into the role of dual tasking on submaximal torque control at the shoulder and its potential importance for injury risk. Additionally, measuring performance changes in both motor and cognitive tasks enabled quantification of dual-task effects and provided insight into participant task prioritisation strategies.

However, several limitations of the study also need to be noted. While our sample size ($n=20$) may have limited statistical power and generalisability, particularly given

the multiple comparisons and non-parametric analyses employed, several lines of evidence suggest the observed differences are nonetheless meaningful. First, the percentage differences between dual and single task conditions for the torque matching task (28–58% for RMS; 51–61% for SD) exceed the 25% difference threshold this study was powered to detect, and align closely with previous investigations of torque steadiness under motor-cognitive dual task conditions in the upper limb (Pereira et al., 2015, 2018). For the torque tracking task, the percentage difference observed was 23%, which approximates the 25% difference threshold. Together, these analyses suggest the findings are meaningful despite the modest sample size, though some effects may have been underpowered, particularly external rotation accuracy where a moderate effect size just failed to reach statistical significance.

A second limitation was that the fixed testing order (single tasks before dual tasks) may have affected performance through both learning effects and shifts in participant concentration. However, it is common for studies utilising dual task paradigms to assess single task performance to establish a baseline prior to assessing dual task performance (e.g. Temprado et al. (2015), Zijdwind et al. (2006)). Additionally, randomisation of the sequence of the torque matching/tracking tasks and a standardised familiarisation across participants helped to mitigate any potential order or learning effects.

We chose to focus on a single 35% MVC target torque level for the isometric torque matching task, in a single testing position. This level of muscle activity is often apparent in the rotator cuff muscles (Day et al., 2012; Huxel et al., 2008; L.-Q. Zhang et al., 2000). Likewise, a single testing position was utilised but is justified in being a limb position of functional relevance and a position at which injuries often occur, particularly in overhead sports and activities (Inui et al., 2009). Additionally, we used only one cognitive task in the form of the word-direction visual Stroop task. This task

was chosen because it provided a level of challenge involving executive function, has measurable performance, and although it has not been utilised previously in this context, it has relevance to attention during sporting activities due to the visual and choice-reaction nature of the task.

In the present study menstrual cycle phase and hormonal contraceptive use were not controlled. This may have introduced unmeasured variability in both motor and cognitive task performance, potentially masking subtle dual-task effects or contributing to individual differences in task prioritisation strategies. Whilst sex differences are known to exist in motor unit behaviour, the effect of hormonal fluctuations, including oral contraception, remains uncertain due to a lack of studies on motor unit behaviour (Lulic-Kuryllo & Inglis, 2022). Similarly, there is very limited evidence of the effect of hormonal status on torque control measures. Knee extensor steadiness during sustained isometric contractions has been demonstrated to be reduced during mid-luteal phase compared with other phases (Tenan et al., 2016). However, aside from the results of Tenan et al., torque steadiness changes across the menstrual cycle remain unknown. This should be investigated in future research to explore whether hormonal changes are correlated with changes in shoulder torque control.

Although participants' sporting activity levels and expertise were recorded, an objective measure such as the International Physical Activity Questionnaire (Craig et al., 2003) may have allowed for stratifying participants by activity levels and to be able to investigate potential differences in task performance. However, self-report measures for physical activity have been shown to have moderate validity at best, with generally low-moderate correlation with direct measures (Helmerhorst et al., 2012; Prince et al., 2008). Importantly though, no participants were considered competitive/elite level overhead athletes, as these populations are known to demonstrate differences in ROM, strength and proprioceptive acuity (Nodehi-

Moghadam et al., 2013) as well as having a high prevalence of persistent shoulder problems (Schwank et al., 2022).

Similarly, although participants were screened for current or significant past shoulder injury, utilising a patient reported outcome measure such as the Shoulder Pain and Disability Index (SPADI) (Breckenridge & McAuley, 2011) would have provided data on any potential symptoms and/or loss of function. However, the participants in this study were a relatively homogenous group with none reporting shoulder pain or a history of shoulder injury so tools such as the SPADI are unlikely to reveal any findings of relevance. Additionally, all participants demonstrated adequate ROM for the test protocols and negative apprehension testing.

Recording EMG activity in the muscle of interest during torque control tasks allows for mechanistic interpretation of the torque control results and potential change in muscle activation strategies. However, few studies have used EMG in torque control studies at the shoulder in non-neurological populations, with those that have not finding any associations between EMG activity and torque control (Bandholm et al., 2006, 2008). This may reflect the methodological challenges of EMG at the shoulder complex. Many different muscles are involved in movements at the GHJ and interpreting their relative contribution to shoulder torque control is challenging.

Surface EMG (sEMG) results are notoriously difficult to interpret in this context, with sEMG prone to large overestimations of rotator cuff activity compared to intramuscular EMG (Waite et al., 2010) and the potential for crosstalk is also likely to influence interpretation (Mesin, 2020; Rathi et al., 2015). Intramuscular fine-wire EMG is therefore preferable, however given the muscles of interest (rotator cuff) and testing position, fine-wire EMG can be problematic, with failure rates of up to 32% with fine-wire EMG of rotator cuff muscles (Heuberger et al., 2015) and issues with accurate placement of electrodes (Rathi et al., 2015).

It must also be acknowledged that musculotendinous stiffness may contribute to individual differences in torque control, even when participants are tested in identical positions. Shoulder passive stiffness can be assessed through methods such as passive torque-angle relationship (Wight et al., 2018) and perturbation displacement (Huxel et al., 2008), and may influence the baseline capacity for torque modulation at the shoulder. However, several considerations guided the decision not to include such measures. First, we aimed to minimise participant burden and limit the number of assessments, which was particularly important given the constraints imposed by the COVID-19 pandemic. Second, while a theoretical relationship between musculotendinous stiffness and torque control exists, this association has not been firmly established in the literature with only one previous study, the author is aware of, investigating this relationship, reporting a negative correlation between ankle plantar flexor torque steadiness and Young's modulus of the Achilles tendon (Johannsson et al., 2015). This correlation was only observed at 5%MVC contractions and not higher intensities. Third, and most importantly, passive stiffness is unlikely to systematically influence cognitive-motor interference, which was the primary focus of our investigation. Nonetheless, future researchers may wish to explore the relationship between passive musculotendinous stiffness and torque control at the shoulder to better characterise individual variability in motor performance.

We made observations on task trade-off and priority based on dual task effect calculations, to provide useful additional insights into participant strategies for allocating attention that may help to guide future research. Statistical analyses were not performed on these metrics as they were considered outside of the main research questions and to avoid further increasing the chance of a Type I error due to the number of statistical comparisons performed. Whilst not formally tested, these descriptive observations are nonetheless consistent with the anticipated pattern of

greater overall dual-task cost during tracking, as discussed above. Furthermore, whilst widely used, dual task effect metrics have been challenged due to a lack of predictive and concurrent validity due to use of a variety of cognitive tasks with greater intra-individual variability and motor tasks that lack adequate re-test reliability, albeit based on a review of locomotor-cognitive paradigms (Pike et al., 2023). As such, these findings should be considered preliminary.

3.6 Conclusion & Future Research Directions

Torque control of the shoulder is impaired in the presence of a secondary visual cognitive task, both during torque matching tasks and torque tracking tasks. The increased amount of error observed in the tracking task may reflect the increased complexity of the motor task. The dual task effect demonstrated a cognitive-priority trade-off when the visual Stroop task was performed with the torque matching task, but mutual interference with the torque tracking task, suggesting participants selectively prioritised their attentional resources to the more complex tracking task.

Future research should systematically investigate dual task performance at the shoulder by varying both motor task complexity (target torque levels, contraction types, joint positions) and cognitive task demands (task modality, complexity, attentional load) to elucidate dual task effects relevant to real-world performance. Specifically, comparing different cognitive task modalities (e.g., auditory Stroop tasks, serial subtraction, n-back working memory tasks) would clarify whether interference patterns are modality-specific or reflect general attentional capacity limitations. Investigating cognitive tasks with varying complexity levels (e.g., simple reaction time vs. choice-reaction vs. working memory tasks) would establish dose-response relationships between cognitive load and shoulder sensorimotor performance. Such research would guide evidence-based task selection for researchers and clinicians seeking to integrate dual tasking paradigms into shoulder injury prevention strategies or rehabilitation programs.

Studies should systematically vary target torque levels (e.g., 20%, 35%, 50%, 70% MVC) to establish whether dual-task interference is consistent across torque magnitudes. Additionally, despite methodological challenges, investigating torque control during dynamic isokinetic contractions at sport-relevant velocities (e.g., 60°/s, 180°/s, 300°/s) may better replicate throwing and overhead activities. Testing across multiple shoulder positions (varying abduction angles and external rotation ranges) would determine whether dual-task effects are position-dependent, particularly in ranges associated with injury risk.

Exploring dual task performance in injured populations may provide valuable insights into clinical relevance. In particular, populations with shoulder instability warrant investigation as they are likely to suffer similar sensorimotor deficits as those observed in ACL injured populations. The more extensive body of research in ACL populations has established the need for a multi systems approach in rehabilitation including sensorimotor control and neurocognition (Chaput, Ness, et al., 2022; Walker et al., 2021).

Implementation in clinical settings could involve progressive dual-task training protocols, beginning with simple cognitive tasks paired with basic torque matching, and advancing to complex cognitive-motor combinations. Clinical outcome measures should include both motor performance (torque steadiness and accuracy) and cognitive performance (reaction time, accuracy) to assess training effectiveness and ensure actual improvement in dual tasking rather than shifting task prioritisation. Investigating whether improvements in dual-task shoulder control transfer to sport-specific skills (e.g., throwing accuracy under pressure, tackling technique with distraction) would establish the ecological validity of such interventions. Additionally, research should examine whether enhanced dual-task performance reduces injury recurrence rates in at risk groups.

Torque tracking tasks warrant further investigation, particularly regarding force modulation and the selective coordination of agonist-antagonist muscle activity, given the co-contraction role of the rotator cuff in centring and controlling humeral head movement during dynamic shoulder tasks. This represents an opportunity to further elucidate the sensorimotor mechanisms underlying torque control and its role in dynamic shoulder function and injury risk.

Future research should also address the methodological limitations of the current study by including larger sample sizes with adequate power to detect small-to-moderate effects, controlling for female hormonal status, and incorporating measures to elucidate the neuromuscular mechanisms underlying dual-task interference at the shoulder.

Chapter 4: The Effect of Local Muscle Fatigue on Submaximal Torque Control at the Shoulder

4.1 Introduction

The glenohumeral joint is commonly injured in sports due to its unique anatomy and wide range of motion, especially in activities involving overhead movements, high velocity, and heavy training loads (Asker et al., 2018). Athletes in contact sports, such as rugby, face additional risks, with tackles representing the highest risk of shoulder injury (S. Williams et al., 2013), and tackling technique being poorer when fatigued (Davidow et al., 2020).

The incidence of shoulder injuries in sport and their burden led to a consensus statement being published (Schwank et al., 2022) to help clinicians and coaches manage the risk of shoulder injuries in sport. This statement, along with other similar recommendations (Eckard et al., 2018; C. M. Jones et al., 2017; Kekelekis et al., 2020; Tripp et al., 2007), identified muscle fatigue as a significant risk factor for shoulder injury, especially in overhead and throwing sports.

Muscle fatigue is defined as an exercise-induced reduction in muscle force generating capacity (Vøllestad, 1997) typically occurring during sustained or repeated contractions. Fatigue is recognised as being both peripheral and central in nature (Boyas & Guével, 2011; Enoka & Duchateau, 2008; Gandevia, 2001). Peripheral fatigue refers to neuromuscular changes at, and downstream of, the neuromuscular junction mediated by muscle metabolic accumulation, excitation-contraction coupling failures and decreases in net synaptic input to motor neurons (Enoka, 2012; Enoka & Duchateau, 2008). Central fatigue relates to reduced voluntary drive to motor neurons within the CNS, which involves factors such as decreased corticospinal excitability, changes in neurotransmitter balance, changes in motivation, perceptions of effort, and nociceptive afferent feedback mediated

inhibition of central drive (Bigliassi, 2015; Gandevia, 2001; Leavitt & DeLuca, 2010; J. L. Taylor et al., 2016; J. L. Taylor & Gandevia, 2008).

While shoulder injuries often occur during dynamic, high-velocity movements, investigating sensorimotor control under fatigue using controlled isometric tasks provides foundational insight into the neuromuscular mechanisms that may contribute to injury risk. Importantly, research shows that even modest isometric muscle activation can substantially increase glenohumeral joint stiffness in the apprehension position. Isometric internal rotation contractions at 50% MVC have been found to increase GHJ stiffness by up to 77% in response to external perturbation (Huxel et al., 2008), while contractions as low as 10% of maximal torque production can still produce a mean 64% increase in stiffness compared with passive levels (Nicolozakes et al., 2021). These results highlight the importance of muscle contractions contributing to stabilising the GHJ particularly in the apprehension position which has been associated with risk of injury.

Static torque control tasks allow for isolated assessment of torque regulation and proprioceptive function without the extraneous sources of torque fluctuation that may occur with dynamic efforts (e.g., stretch reflex loops, dynamometer mechanical vibration; Clark et al. (2023). Understanding how fatigue affects these fundamental control mechanisms may provide direction for the assessment of shoulder stability under more complex loading conditions.

Specifically, muscle fatigue is considered to hamper sensorimotor control and lead to functional instability at the GHJ (Myers et al., 1999; Tripp et al., 2007), which in turn can lead to undesirable movement and forces occurring across the joint, ultimately predisposing it to injury. Fatigue-induced changes in sensorimotor control include; declines in kinaesthetic proprioceptive acuity, particularly joint position sense (JPS), due to decreases in muscle spindle thixotropic state and sensitivity leading to altered

processing of afferent signals from fatigued muscles (Proske, 2019; Proske et al., 2014); alterations in motor recruitment strategies (Enoka, 2012; Enoka & Duchateau, 2016); and reduced sensorimotor responsiveness due to delays in CNS processing (J. L. Taylor et al., 2016). Fatigue may also influence the ability to control task specific and precise levels of torque during functional tasks and exercise (Pethick & Tallent, 2022).

While most shoulder fatigue research has focused on JPS, a recent systematic review and meta-analysis (Takasaki et al., 2016) of 12 studies found that shoulder muscle fatigue impairs active JPS primarily in outer ranges of external rotation, but not for other movements or positions. However, these studies employed highly variable fatigue protocols, ranging from sustained maximal contractions to sport-specific tasks, and inconsistent definitions of fatigue. Critically, none examined torque control measures such as steadiness or accuracy, leaving this aspect of sensorimotor function unexplored at the shoulder.

The effect of fatigue on torque matching accuracy has yielded conflicting findings across the literature, with discrepancies evident in studies of both the upper and lower limbs. While some upper limb studies demonstrate impaired force sense following eccentric exercise, with participants either overestimating (Carson et al., 2002) or underestimating (Proske et al., 2004) the force generated by fatigued muscles, the mechanisms remain debated. Lower limb findings are similarly mixed, with fatigue degrading ankle force sense (Vuillerme & Boisgontier, 2008; C. J. Wright & Arnold, 2012) but not at the knee extensors (Allison et al., 2016).

At the shoulder, Coskun et al. (2018) found no effect of isokinetic fatigue on 50% MVC torque matching in young males. However, their protocol involved a hand-grip attachment (potentially providing extraneous cutaneous feedback and force contributions), a brief 3-second analysis window, and extended post-fatigue testing

without verification of maintained fatigue, limitations that may have obscured genuine effects.

These discrepancies likely stem from methodological variations in fatiguing protocols (sustained vs intermittent, isometric vs isokinetic, laboratory vs functional tasks), post-fatigue assessment timing, target force levels, and sensory feedback conditions. Critically, **no studies have examined torque steadiness at the shoulder**, a measure consistently demonstrated to be sensitive to fatigue at other joints (Enoka & Duchateau, 2008; Pethick & Tallent, 2022).

Multisensory integration enables the central nervous system to shift reliance between sensory sources when one becomes less reliable (Tagliabue & McIntyre, 2014). Visual feedback provides real-time error correction, consistently improving torque matching accuracy (Baweja et al., 2009, 2010, 2011; E. J. Fox et al., 2013), whereas its removal necessitates reliance on proprioceptive inputs. Critically, visual feedback can protect against the detrimental effects of external stressors on torque control, for instance, fatigue significantly increasing torque matching error but only in the absence of visual feedback (Kiyama et al., 2014). As previous shoulder studies have not compared between visual feedback conditions, the current study included both to examine whether visual feedback attenuates the influence of fatigue on torque control and whether its removal reveals proprioceptive contributions that might otherwise be masked.

The present study builds on previous studies in several ways. First, we employed a duty-cycled intermittent fatiguing protocol that produces sustained peripheral and central fatigue whilst minimising excessive metabolic accumulation and verified fatigue through Borg scores and repeat MVC testing. Second, we examined torque steadiness, a measure previously shown sensitive to fatigue at other joints (Enoka & Duchateau, 2008; Pethick & Tallent, 2022) but never investigated at the shoulder.

Third, we tested in the apprehension position where rotator cuff stabilisation demands are heightened (Labriola et al., 2005) and the GHJ is in outer ranges of external rotation, where fatigue-related decrements in JPS have previously been observed (Takasaki et al., 2016). Finally, we systematically compared visual feedback conditions to isolate proprioceptive contributions that may be masked when visual feedback is available.

4.1.1 Aims

Given these methodological refinements and the current evidence for fatigue effects on torque control predominantly at other joints, the aim of this study was to investigate the effect of a duty-cycled 60% MVC isometric fatiguing task on measures of isometric torque steadiness and torque matching accuracy for shoulder internal rotation only. We hypothesized that after the fatiguing protocol, an increase in both SD (decreased steadiness) and RMS (decreased accuracy) under both visual feedback conditions. Given evidence that visual feedback can attenuate sensorimotor deficits (Christou, 2005; Kiyama et al., 2014), these decreases were expected to be significantly greater in the absence of visual feedback, where participants rely predominantly on proprioceptive sense of force. Based on the consistent findings of fatigue-related changes in torque steadiness, but inconsistent evidence for an effect on torque matching accuracy, we expected to observe greater increases in SD than RMS.

4.2 Methodological Considerations

4.2.1 Common Considerations

The methodological considerations for the common aspects of the torque control tasks are discussed in Chapter 3: isometric peak torque (Section 3.2.1, p.95); task selection (Section 3.2.2, p.96); target torque levels (Section 3.2.3, p.97); testing position (Section 3.2.4, p.98), limb dominance (Section 3.2.5, p.99); cutaneous sensory influence (Section 3.2.6, p.100); visual gain (Section 3.2.7, p.101); and

learning effect (Section 3.2.8, p.102). The methodological considerations unique to this chapter are discussed in detail below.

4.2.2 Torque control and Visual feedback

Multisensory integration is the process by which the brain integrates sensory information from multiple sources to estimate environmental variables such as limb position and force output (Sober & Sabes, 2005; Stein & Rowland, 2011). When one source of sensory input becomes less reliable, either due to the introduction of noise in its sensorimotor processing (i.e. neural noise from additional processing demands) or due to removal of that source, the CNS can shift its reliance to alternative sources of sensory information (Tagliabue & McIntyre, 2014). Investigating torque control with and without visual feedback therefore allows inference regarding the relative influence of visual versus proprioceptive sensory inputs on motor performance.

Visual feedback provides real-time information about performance allowing for ongoing error detection and correction via a closed-loop mechanism. Visual feedback is therefore a potent mechanism for improving torque matching performance. However, reliance on visual feedback may lead to dependence on visual stimuli reducing adaptability to contexts where visual information is not available.

Removing visual feedback provides insight into the proprioceptive component of sensorimotor control. Torque matching without visual feedback is an example of an open-loop feedforward mechanism whereby an individual attempts to match a previously presented target torque based on internal representations and proprioceptive afferent input rather than visual error correction. This approach may have greater ecological validity, as individuals frequently cannot rely on continuous visual feedback during dynamic movements, particularly in sporting contexts where visual attention is directed toward targets or opponents rather than the moving limb itself. In the absence of visual feedback, torque matching accuracy is related to

proprioceptive sense of force (Proske & Allen, 2019), though a declining drift in produced torque commonly occurs when visual feedback is removed (Ambike et al., 2016; Limonta et al., 2015; Vaillancourt & Russell, 2002), suggesting proprioceptive inputs alone may be insufficient for maintaining accurate torque matching.

Findings comparing visual feedback conditions reveal differential effects on torque steadiness and accuracy. Torque steadiness is often improved in the absence of visual feedback across both smaller muscle groups such as the finger flexors (Baweja et al., 2009) and larger muscle groups such as the quadriceps and elbow flexors (Tracy, Mehoudar, et al., 2007), although other research at the muscles of the finger has shown no effect of visual feedback removal on steadiness (Christou et al., 2004; Vaillancourt & Russell, 2002). Conversely, torque matching accuracy is consistently reduced when visual feedback is removed (Baweja et al., 2009; Limonta et al., 2015; Tracy, 2007; Tracy, Dinunno, et al., 2007; Vaillancourt & Russell, 2002; Welsh et al., 2007). Importantly, visual feedback can protect against the detrimental effects of external stressors like experimentally induced pain on torque control (Christou, 2005). Similarly, fatigue has been demonstrated to significantly increase torque matching error only in the absence of visual feedback (Kiyama et al., 2014), indicating that sense of force plays a significant role in torque control when visual information is unavailable.

Previous shoulder studies have predominantly used a visual feedback only condition for investigating torque steadiness (Bandholm et al., 2006, 2008; Camargo et al., 2009; Saccol et al., 2014; Zanca et al., 2010) or used visual then non-visual feedback as part of a force reproduction protocol without comparing between conditions (Coskun et al., 2018; Maenhout et al., 2012; Troussset et al., 2018). The inclusion of both visual and non-visual feedback conditions enables examination of two related questions: first, whether visual feedback attenuates the influence of altered proprioceptive input on torque control, and second, whether the absence of

visual feedback unmasks proprioceptive contributions to motor performance that would otherwise be masked.

Given this evidence, the current study included both visual and non-visual feedback conditions to examine whether visual feedback attenuates the influence of fatigue on torque control, and whether removing visual feedback reveals changes in proprioceptive contributions to shoulder torque control that might otherwise be masked. Both torque matching accuracy and torque steadiness were assessed under each feedback condition to capture the differential effects of visual feedback on these distinct aspects of sensorimotor control.

4.2.3 Contraction type and intensity

Fatigue can be induced through various contraction types, each with distinct advantages and limitations. Isokinetic protocols offer controlled velocity but an attempt at a standardised protocol (Roy et al., 2011) yielded inconsistent results at the shoulder, with no significant decline in isokinetic peak torque despite modest isometric MVC reductions (-22% flexors, -17% external rotators). Functional protocols such as repeated overhead movements (Ebaugh et al., 2006b, 2006a) or throwing tasks (Andrade et al., 2016; Dale et al., 2007) may better simulate sport or vocational-specific demands but are difficult to standardise across participants and obscure which specific muscles are fatigued. Critically, fatigue mechanisms differ dependent on task demands and muscle groups (Hunter, 2018; Krüger et al., 2019), meaning that fatigue induced isokinetically may not transfer to isometric performance measures and vice versa as has been previously observed at the shoulder (Roy et al., 2011). An isometric protocol was therefore selected to ensure valid pre-post comparison using the same contraction type for both fatigue induction and torque control assessment.

Within isometric protocols, a fundamental choice exists between sustained and intermittent contractions. Sustained contractions induce rapid fatigue through

vascular occlusion, creating metabolic conditions (disproportionate lactate and inorganic phosphate accumulation) that differ substantially from typical muscle activity (McPhee et al., 2014; Pethick & Tallent, 2022). This occlusion prevents the partial phosphocreatine resynthesis and metabolite clearance that occur during recovery phases integral to most physical activities. Intermittent protocols, by contrast, permit cycles of muscle reperfusion and partial energy regeneration between contractions, more faithfully reproducing cyclic characteristic of activities such as repeated overhead tasks, throwing, tackling, or manual labour tasks (McPhee et al., 2014). The relative contribution of central versus peripheral fatigue pathways is sensitive to metabolic conditions under which fatigue develops, making the structural similarity between intermittent protocols and real-world muscle activation patterns important for construct validity.

Several studies at the quadriceps have successfully employed intermittent protocols with 60% duty cycles (work:rest) at intensities of 40-60% MVC (Ansdell et al., 2017; Pethick et al., 2015, 2016, 2018). At the shoulder, intermittent protocols have varied widely in both intensity and duty cycle (Hermans & Spaepen, 1997; Iridiastadi & Nussbaum, 2006; Looft & Frey-Law, 2020; Mehta & Agnew, 2012). Importantly, the combination of intensity and duty cycle determines both time-to-fatigue and the underlying mechanisms of neuromuscular impairment. For instance, Iridiastadi & Nussbaum (2006) demonstrated that while EMG amplitude was insensitive to changes across protocols, spectral analyses (median and mean power frequency shifts) revealed that higher intensities (28% vs 12% MVC) combined with greater duty cycles (75% vs 25%) produced more rapid changes in motor unit recruitment and firing patterns, indicative of combined peripheral and central fatigue. Similarly, recent work examining intensity-duty cycle interactions shows that higher intensities require recruitment of larger motor units and higher firing rates, producing greater metabolite accumulation, while higher duty cycles limit recovery time, compounding

both peripheral metabolic stress and central fatigue from sustained motor commands (Looft & Frey-Law, 2020; Muddle et al., 2018).

A key methodological challenge is selecting an intensity that reliably induces measurable fatigue within practical timeframes while maintaining physiological relevance. Research has identified a 'critical torque' (CT) threshold above which fatigue develops 4-5 times faster than below it (Burnley et al., 2012). At the quadriceps, the CT occurs at approximately 30% MVC, with 40% MVC reliably inducing fatigue within ~11.5 minutes, while 20% MVC fails to produce measurable fatigue within 30 minutes (Pethick et al., 2016, 2019). Contractions performed below the CT are associated with small changes in muscle metabolite concentrations, while contractions above the CT are associated with progressive loss of muscle metabolic homeostasis playing a key role in the development of peripheral fatigue above the CT.

At the shoulder, no CT threshold has been established, and existing studies demonstrate highly variable time-to-fatigue depending on intensity-duty cycle combinations. Time-to-fatigue ranges from 1 minute 9 seconds with 70% MVC at 70% duty cycle (Looft & Frey-Law, 2020) to 58 minutes 18 seconds with 30% MVC at 50% duty cycle (Iridiastadi & Nussbaum, 2006). These variations reflect not only differences in protocol parameters but also the underlying fatigue mechanisms engaged.

Selection of 60% MVC for the present study was based on converging evidence and physiological principles. This intensity: 1) reliably exceeds CT thresholds established at other joints (~30% MVC), ensuring fatigue development within practical timeframes for data collection (Allman & Rice, 2001; Looft & Frey-Law, 2020; Pethick et al., 2016); 2) minimises participant burden and reduces confounds from declining motivation or concentration over extended protocols; 3) recruits both smaller and

larger motor units, producing combined metabolic and neural fatigue necessary for understanding sensorimotor control changes (Allen et al., 2008; J. L. Taylor & Gandevia, 2008); and 4) approximates muscle activation levels documented during overhead sporting activities (Escamilla & Andrews, 2009). Combined with a 60% duty cycle (6s:4s work:rest), this protocol balances experimental control, physiological validity, and practical feasibility, though empirical determination of shoulder-specific CT remains a priority for future research.

4.2.4 Measurement of fatigue

Within the musculoskeletal literature, there is no consistent method for quantifying and ensuring fatigue, as has been highlighted in systematic reviews (Santamaria & Webster, 2010; Takasaki et al., 2016). In the absence of true 'gold-standard' measurements of muscle fatigue, recommendations of valid and reliable measures such as MVC force or power output have been made (Vøllestad, 1997).

Measurement of decline in isometric MVC aligns well with most used definitions of fatigue as being exercise-induced reductions in MVC force (Place & Millet, 2020).

Submaximal isometric tasks at 50%MVC have shown comparable decreases in MVC of between 30 and 40% across different muscle groups (Neyroud et al., 2013). At the shoulder, an intermittent 50%MVC 50% duty cycled task resulted in a mean drop in MVC of ~32% (Looft & Frey-Law, 2020).

Electrically invoked twitches that are performed during and after isometric MVCs (Place & Millet, 2020; Vøllestad, 1997) can provide evidence of peripheral and central fatigue, but these require additional training and familiarisation of subjects to tolerate the electrical impulses which can invoke notable discomfort. Furthermore, placement of stimulation electrodes, particularly those that are stimulating nerves can be time consuming given individual differences in anatomy. Additionally, there is limited previous literature concerning the validity and reliability of such testing for internal and external rotators of the shoulder. Given the origin and insertion of these

muscles, it would also be difficult to be sure of generating electrical pulses in the appropriate muscles that were being fatigued.

Pragmatically, studies have also used other measures of fatigue such as task failure and rate of perceived exertion (RPE) (Borg, 1998). As a useful self-measure of workload, RPE has been used in numerous studies and has previously been shown to correlate well with exertional heart rate ($r=0.74$) and blood lactate ($r=0.83$) (Scherr et al., 2013). Task failure, whilst convenient, may be influenced by an individual's motivation and may therefore not be an accurate representation of muscle fatigue, especially if no post-protocol objective testing is conducted. For instance, a recent systematic review (Takasaki et al., 2016) on fatigue and shoulder proprioception excluded four studies specifically because the absence of a fatigue definition made it impossible to verify that participants were genuinely fatigued following the described protocols. Re-assessing MVC following the post-fatigue testing period can demonstrate that fatigue has been sustained adequately for the testing period as has been adopted previously (Missenard et al., 2009).

In summary, a combination of fatigue determinants - task failure, objective measures (isometric MVC testing), and subjective measures (RPE) - allows for different aspects of fatigue to be characterised and may better represent real-world fatigue than a single measure (Place & Millet, 2020).

4.2.5 Fatigue duration

A further consideration for fatigue protocols is the duration of the fatigue effect and its measurement. A key aspect of a fatigue protocol is that participants remain sufficiently fatigued for the subsequent testing period. In a study by Vøllestad et al. (1997) who tested the quadriceps using a fatiguing protocol with a 60% duty cycle and at 60%MVC, immediate post-fatigue quadriceps MVC dropped to $63\pm 2\%$ of pre-fatigue MVC, and this recovered $88\pm 3\%$ by the end of a 27-minute total rest period.

Research at the elbow flexors (Allman & Rice, 2001) showed that within three minutes of completing a fatiguing protocol of intermittent isometric contractions at 60% MVC, participants' force production rapidly returned to within 83% of the pre-fatigue MVC. By the end of a 60-minute recovery window, MVC was still significantly reduced compared to pre-fatigue but had increased steadily to $94\pm 4\%$ MVC for younger males and $91\pm 3\%$ for older males. Previous research of fatigue at the shoulder (Lee et al., 2003) has also highlighted the need to conduct post-fatigue tasks as quickly as possible to reduce potential confounding effects of muscle recovery.

Given that the duration of fatigue is not consistently demonstrated in the literature, determining a suitable and pragmatic washout period is difficult. This makes randomised crossover designs challenging and is perhaps a reason why studies typically employ a repeated measures design. The variable reporting of fatigue confirmation and duration in the literature, supports repeating MVC testing following the fatigued-state testing period to confirm sufficient fatigue for the duration of the post-fatigue data collection.

4.2.6 Task selection

The transient nature of exercise-induced fatigue necessitated prioritising post-fatigue measures to capture genuine fatigue effects before recovery processes attenuate them (Allman & Rice, 2001). Accordingly, testing was strategically limited to internal rotation torque matching.

Internal rotation was selected for its functional relevance in the testing position employed. As outlined in the introduction, even modest isometric muscle activation can significantly enhance GHJ stiffness, particularly in the apprehension position, with internal rotation contractions at 50% MVC increasing GHJ stiffness by up to 77%, while contractions as low as 10% of maximal torque still produce a mean 64%

increase compared to passive levels. Electromyogram studies have demonstrated the significant role of subscapularis as a primary anterior stabiliser, functioning quasi-isometrically to resist perturbing forces (Day et al., 2012; Rathi et al., 2016; Wattanaprakornkul et al., 2011). These findings make internal rotator function particularly pertinent for understanding shoulder torque control under fatigue.

Focusing on a single rotation direction also offered methodological advantages. Internal and external rotators demonstrate differential fatigue characteristics across different populations (Ellenbecker & Davies, 2000; Ellenbecker & Roetert, 1999; Hawkes et al., 2015; Klich et al., 2021), meaning that testing both directions would require more complex fatiguing protocols and introduce additional variability in fatigue states, potentially confounding interpretation of results.

Torque tracking was excluded for related reasons. The tracking task requires alternating between internal and external rotation to follow a sinusoidal target (see Section 3.3.11, p.116) which would necessitate fatiguing both muscle groups equivalently. This requirement would be difficult to achieve given their differential fatigue profiles. The static torque matching protocol therefore provided a more controlled approach for isolating fatigue effects on submaximal torque control.

In summary, given concerns regarding fatigue duration and recovery, post-fatigue testing was limited to a single rotation direction (internal rotation) and focused on torque matching and steadiness rather than torque tracking. Internal rotation was prioritised due to the stabilising role of isometric internal rotation in the testing position employed, whilst the static torque control measures maintain consistency with the established fatigue literature at other joints (Pethick & Tallent, 2022).

4.3 Methods

4.3.1 Study Design

A repeated measures, within-subject experimental design was used to investigate the effect of local muscle fatigue on shoulder isometric torque control in a population of healthy young adults. Data for this study was collected concurrently with the study presented in Chapter 5.

4.3.2 Ethical Approval

Ethical approval was provided by the New Zealand Health and Disability Ethics Committee (HDEC) (reference 21/NTB/98) and Auckland University of Technology Ethics Committee (AUTEK) (reference 21/348).

4.3.3 Sample Size Calculation

Sample size calculations were performed in G*Power v3.1.9.6 (Faul et al., 2007). There was no existing literature deemed sufficiently similar to the planned study to base our sample size calculation on. Hence, pilot testing (n=6, 3M:3F, Age Range 20-29) was completed before data collection began to establish means and SDs, using the test procedures described in Section 4.3.9. The variables of interest were internal rotation steadiness (SD) and accuracy (RMS error) during torque matching (with visual feedback) under baseline torque matching variability only and did not include the fatiguing protocol. The participants in the pilot study were representative of the study cohort in age and health status, and no pilot participant was included in the final study sample. The dependent variables of interest were (1) internal rotation steadiness (SD) and accuracy (RMS error) during torque matching (with and without visual feedback).

For torque matching, the mean (\pm SD) for steadiness and accuracy were 0.32 ± 0.14 Nm and 0.35 ± 0.17 Nm respectively. For all sample size calculations, two-tailed tests were utilised, with an α level of 0.05, power of 80%, and an estimated correlation between repeated measures of $r=0.7$. Whilst no studies have

investigated fatigue effects on torque control variables of SD or RMS at the shoulder, previous research at the knee (Pethick et al., 2016), demonstrated a mean 75% and 95% difference in SD and RMS respectively (with visual feedback) following a comparable intermittent submaximal fatiguing protocol to the present study. As shoulder torque control tasks differ in complexity and attentional demand, to detect a more conservative 25% difference in the variables of interest between pre- and post-fatigue conditions (matched pairs), sample size calculations yielded $n=20$ for torque matching RMS and $n=17$ for torque matching SD. The largest required sample ($n=20$) was used to determine the recruitment target. To account for a maximum dropout rate of 10%, the recruitment target was set at 22. A 25% change corresponds to an absolute between condition difference of 0.09 for torque matching RMS ($d=0.51$) and 0.08 for torque matching SD ($d=0.57$). Pilot testing in the same cohort ($n=6$) established excellent test-retest reliability for torque RMS ICC=0.99, 95%CI [0.92,1.00], SEM=0.02, and torque SD ICC=0.95, 95%CI [0.66,1.00], SEM=0.03. Using these values, the minimum detectable change for the group differences (MDC_{GROUP}) was calculated as 0.01 for RMS and 0.02 for SD for the torque matching task. ($MDC_{GROUP} = (SEM \times 1.96 \times \sqrt{2}) / \sqrt{n}$, where $n = 20$). Importantly, the target between-condition differences used in the power calculations exceeded their respective MDC_{GROUP} values by factors of 9.0 and 4.0 respectively, indicating that the measurement approach utilised possesses sufficient sensitivity to detect the minimum effects for which the study was powered.

4.3.4 Participant Recruitment

Twenty-one healthy volunteers were recruited via recruitment posters placed on university noticeboards and snowball sampling. A cohort of young adults was sought to represent an active population likely to participate in sports/activities with an inherent risk of shoulder injury, and where torque control at the shoulder may be important. Potential participants were screened for inclusion and exclusion criteria

via phone conversation by the principal investigator. Those participants who met the inclusion and exclusion criteria were invited to participate via consecutive sampling. All participants provided written informed consent prior to commencement of data collection and were then considered enrolled in the study.

4.3.5 Inclusion/Exclusion Criteria

The following inclusion and exclusion criteria were applied:

Inclusion: Individuals aged 20-35 years, without history of shoulder injury (criteria for shoulder injury were any shoulder or upper arm symptoms that had necessitated input from a health care professional).

Exclusion: Current or past upper limb or spinal pathology that required management by a health professional, history of a neurological condition, other forms of global joint pathology (e.g. hypermobility syndrome, arthropathies), and non-fluency in the English language.

Prior to data collection, participants were screened for shoulder ROM and the apprehension test (Tzannes & Murrell, 2002). This screening was performed by the principal investigator, a physiotherapist with over 20 years of clinical experience. All participants demonstrated sufficient GHJ ROM for the testing protocol (90° of abduction and 90° external rotation) and none demonstrated significant hypermobility (>180° of total rotation in 90° abduction (Nicholson & Chan, 2018)) or a positive shoulder apprehension test.

4.3.6 Participant Characteristics

A questionnaire created in REDCap (Research electronic data capture (Harris et al., 2009)) was used to collect patient characteristics such as age, height, weight, and ethnicity. Defining sports participation and expertise varies considerably in the literature, especially across sports (Swann et al., 2015). Therefore, sports participation was defined pragmatically (social=recreational e.g. friends and family;

competitive = take part in organised league or events; elite = representative (e.g. region/national). No participants participated in competitive or elite level overhead sports defined as 'a sport in which an athlete, with the forearm/hand lifted above the head, repetitively propels a ball or shuttle against an opponent or a teammate' (Asker et al., 2018).

4.3.7 Experimental Set-up

The dominant shoulder was used as the test shoulder for all participants. Limb dominance was ascertained by asking which hand participants write with.

Participants were then positioned in the Biodex dynamometer (Biodex 3, Biodex Medical Systems, Shirley, NY, USA) with the GHJ positioned in 90° elevation in the scapula plane, 80° external rotation, and the elbow at 90° of flexion and aligned with the dynamometer (for more detail, see Chapter 3, Section 3.2.4).

4.3.8 Warm-up and Shoulder Peak Torque

The previously described warm-up and peak torque procedures (Chapter 3, section 3.2.8) were used. Briefly, after a standardised general shoulder warm-up, two 5-second submaximal contractions were performed at 25%, 50% and 75% perceived maximum effort. Three maximal effort contractions with verbal encouragement were then undertaken for GHJ internal rotation, and the greatest of those three efforts was taken as the participant's MVC. A familiarisation with the equipment and the torque matching task was also part of the warm-up.

4.3.9 Torque Matching Task

As described in Chapter 3 (Section 3.3.10), real time torque data was displayed on the PC monitor set-up as per the MVC testing. Participants were required to wear glasses or contact lenses if normally worn at such a distance. A target torque of each participant's 35% MVC was displayed as a horizontal line centred on the screen by setting the y-axis accordingly. Participants followed the previously outlined process where an indicator light signalled to them to generate torque to the target level and

then hold as steadily as possible for 10 seconds. Immediately following this task, visual feedback was removed, and participants were asked to match the target torque based on their sense of effort, indicating when they felt they had reached the target by depressing an indicator button. This process, with each trial alternating between visual feedback and no feedback, was repeated five times with 30-second breaks between trials.



Figure 14. An example of a participant 35% MVC torque matching trial (*y-axis represents torque [Nm], x-axis represents time [seconds]; black line represents the target torque line, the purple line is the participant's torque; the left curve is with visual feedback, the right is without visual feedback*).

4.3.10 Fatigue Protocol

After completing the baseline torque matching task (eyes open and eyes closed), an intermittent isometric torque matching task of the GHJ internal rotators was used to induce fatigue. Participants were required to match a target torque at 60% of their MVC using a 60% duty cycle (six seconds contraction to four seconds rest). The epochs for matching and rest were signalled by a smartphone application (Seconds, Version 3.22.3). This task was repeated continuously until task failure, defined as when they could not match the 60% MVC target line for an entire 6-second contraction for two contractions in a row. At task failure, participants were asked to provide a modified Borg score on a 0 (no effort) to 10 (maximal effort) scale (Borg, 1998) and immediately performed a post-fatigue MVC (of ~five seconds in duration).

Early pilot testing in our lab established that this protocol resulted in substantial participant fatigue (>20% reduction in MVC) in a pragmatic timeframe (<5 mins). Immediately following this MVC, the target torque matching task was repeated as per Section 4.3.9 above (five trials with visual feedback present immediately followed by visual feedback removed) and thereafter followed by a final MVC to establish if fatigue was still present.

4.3.11 Data Sampling

The analogue torque signal from the dynamometer was transmitted to an analogue/digital data acquisition unit (instruNet Model 100B, GW Instruments Inc., Charleston, MA, USA), sampled at 1000Hz and displayed on a PC via a custom-built software program (DASYLab® v.2016, National Instruments, Ireland). The signal was filtered using a 20Hz low-pass fourth order Butterworth filter. Given the duration of recorded torque signals, this allowed for filtering of undesirable signal noise but also ensured the signal was not overly smoothed (Thompson, 2019). At the same sampling rate, analogue signals (3-volt pulse) associated with the start of the trial and when the participant thought they had reached their target torque, were also transmitted to the data acquisition unit on separate channels.

4.3.12 Data Processing

Data were inspected visually and saved for further analyses. All data were processed offline, and the relevant variables of interest recorded and entered into a spreadsheet (Microsoft® Excel for Mac v16.84). These data were then screened for any inputting errors or omissions.

4.3.13 Dependent Variables

For the torque matching task with visual feedback, torque steadiness was measured as standard deviation (Santos et al., 2016) of the participant torque around the mean torque value over the central six seconds. Torque matching accuracy was measured as the Root Mean Square (RMS) error (Trousset et al., 2018) over the same epoch.

For the torque matching task with no visual feedback, steadiness and matching accuracy were recorded as per the visual feedback condition. For all torque matching task measures, an average of the five trials was used.

4.3.14 Statistical Analyses

Descriptive analyses were performed, and the normality of the distribution of the outcome variables was tested using Shapiro-Wilk tests. Only torque matching steadiness was normally distributed. Thus, for torque matching steadiness, a two-factor repeated measures ANOVA was used to compare means by condition (fatigue status x visual feedback). Main effects and interactions were assessed. Paired samples t-tests were used to determine where differences lay if any interaction was identified. For non-normally distributed data, Wilcoxon signed-rank (WSR) tests were used to compare means across the task condition (fatigue vs no-fatigue) for RMS error. For WSR tests, r effect sizes were calculated using the formula: $r = \frac{z}{\sqrt{N}}$ (where r =effect size, z =z statistic, and N =number of observations), with the effect sizes interpreted as: small=0.10, medium=0.30, large=0.50 (Rosenthal, 1994). For paired t-tests, Cohen's d was used for effect size calculation with interpretations of small=0.2, medium=0.5, large=0.8 as suggested by Cohen (2013). Effect sizes were calculated for ANOVA analyses using partial eta squared (η_p^2) with the effect sizes interpreted as small=0.01, medium=0.06 and large=0.14 (Richardson, 2011).

Additionally, comparison of baseline, immediately post-fatigue protocol, and post torque control assessment task MVC were compared with a repeated measures ANOVA, and if significant, paired t-tests were utilised for comparing (1) baseline MVC with immediate post-fatigue MVC and (2) baseline MVC to post-torque control assessment MVC. An alpha level of $p < 0.05$ was used for all statistical analyses.

Due to multiple comparisons, a family-wise error rate is introduced, that is the probability of a Type I error (i.e. rejecting the null hypothesis when it is true). In

accordance with previous literature, a percentage error rate (PE) was calculated which reflects the proportion of statistically significant results that are likely to be Type I errors (Ottenbacher, 1991). The percentage error rate was calculated using the formula: $PE=100 \times c\alpha/m$ (where c is the number of comparisons, α is the α set for the individual comparisons, and m is the number of tests equal to or less than the α rate). This is an accepted alternative method to using the Bonferroni adjustment for multiple tests, which has previously been acknowledged as increasing potential Type II errors (Perneger, 1998).

4.4 Results

A total of 21 potential participants were recruited for the study. One participant was excluded prior to data collection due to an autoimmune condition that could affect perception of fatigue. The remaining 20 participants (see Table 7) provided written informed consent and completed all data collection. No adverse effects were reported.

Table 7. Baseline characteristics across all participants, n=20 (data presented as mean \pm one standard deviation, or as number/proportion as a percentage)

Characteristic	N ^o ./Proportion	Characteristic	N ^o ./Proportion
Gender	11(55%) Male 9(45%) Female	Sports	
Age (yrs)	24.35 \pm 4.45	Weight training	4(20%)
Height (cm)	171.55 \pm 8.66	Football	3(15%)
Weight (kg)	71.05 \pm 11.48	Hockey	2(10%)
BMI (kg/m²)	23.95 \pm 2.23	Golf	2(10%)
		ARL	1(5%)
MVC (Nm)		Kite surfing	1(5%)
Internal Rotation	36.4 \pm 12.4	Netball	1(5%)
External Rotation	28.9 \pm 11.9	Squash	1(5%)
		Cheerleading	1(5%)
Handedness		Tennis	1(5%)
Right	18(90%)	Cricket	1(5%)
Left	2(10%)	Running	1(5%)
		None	1(5%)
Ethnicity		Level	
NZ European	12(60%)	Social	9(45%)
Other European	2(10%)	Competitive	9(45%)
Southeast Asian	3(15%)	Elite	1(5%)
Latin American	1(5%)	N/A	1(5%)
Middle Eastern	1(5%)		
African	1(5%)		

4.4.1 Fatigue Task

Participants took a mean time to fatigue of 2 mins 58secs (\pm 1.05). Their baseline and post-fatigue task MVC and modified Borg scores can be found in Table 8. Repeated measures ANOVA revealed a main effect for fatigue on MVC ($F=48.63$, $p<0.001$, $\eta_p^2=0.73$). There was a mean decrease in MVC from baseline to immediate post-fatigue test of 10.1Nm (95% CI [6.3, 13.0] $p<0.001$), representing a mean 30% reduction in MVC. From baseline to following the fatigued torque matching tasks, a mean decrease in MVC of 12.8Nm (95%CI [7.8, 15.6], $p<0.001$) was observed, reflecting a 34% (range 16% to 54%) reduction. The mean modified Borg score immediately post-fatigue was 9.7/10 (range 9 to 10) indicated that participants were typically working almost maximally at task failure.

Table 8. Participant shoulder internal rotation MVC and modified Borg scores by condition/task

Variable	Baseline	Post-Fatigue	End of Protocol
Internal Rotation MVC (Nm)	34.6±12.4	24.5±9.1*	21.8±7.9*
Modified Borg Score	0.2±0.6	9.7±0.4	N/A

Note: Data presented as mean±SD; *denotes significant difference from baseline $p<.001$

4.4.2 Torque Steadiness

Two-way ANOVA analysis revealed a main effect for visual feedback on steadiness ($F(1,19)=44.12$, $p<.001$, $\eta_p^2=.70$) but no significant effect of fatigue ($F(1,19)=2.253$, $p=.15$, $\eta_p^2=.11$). No interaction effect was observed ($F(1,19)=0.13$, $p=.72$, $\eta_p^2=.007$).

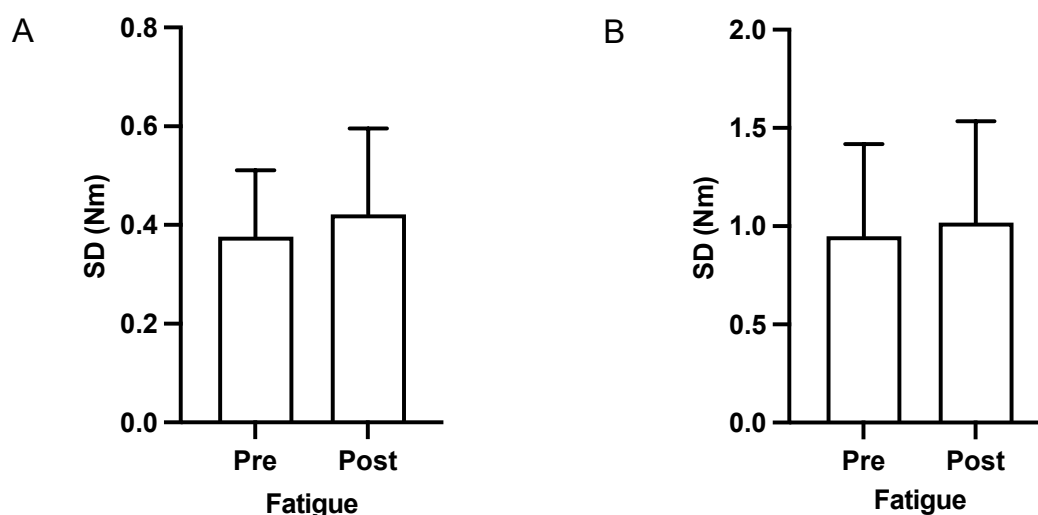


Figure 15. Box and Whisker plot torque steadiness (SD) for the 35% MVC torque matching task by fatigue condition (pre- and post-fatigue protocol). Panel A shows the results with visual feedback, and Panel B without visual feedback (Means and SD shown). Note: lower SD represents steadier torque.

4.4.3 Torque Matching Accuracy with Visual Feedback

Wilcoxon Signed Rank tests showed no statistically significant effect for fatigue on torque matching accuracy (RMS) with visual feedback ($z=-0.56$, $p=0.58$, $r=-0.13$).

4.4.4 Torque Matching Accuracy without Visual Feedback

Similarly, WSR tests found no statistically significant effect for fatigue on torque matching accuracy without visual feedback ($z=-0.50$, $p=.61$, $r=-0.11$).

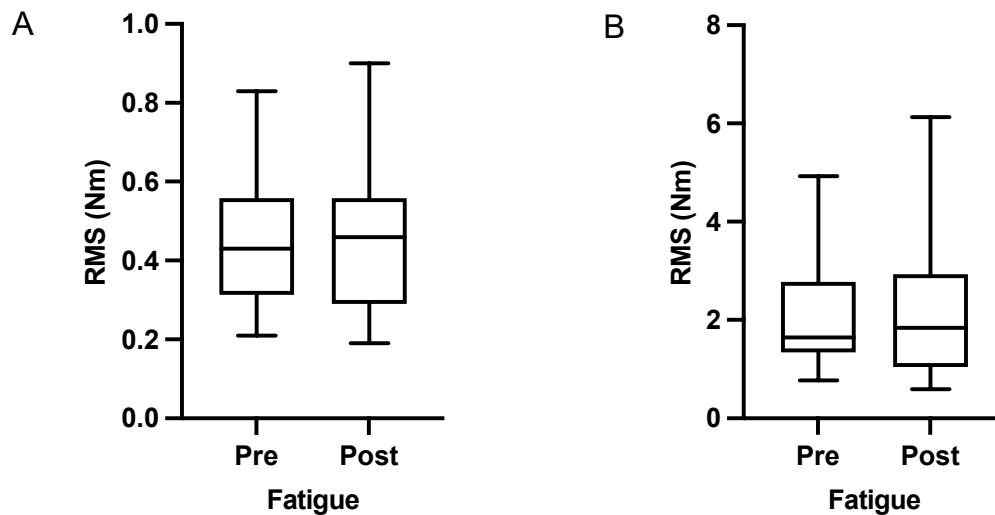


Figure 16. Box and Whisker plot showing torque matching accuracy (RMS Error) for the 35% MVC torque matching task by fatigue condition (pre- and post-fatigue protocol). Panel A shows the results with visual feedback, and Panel B without visual feedback (medians and interquartile ranges shown). *Note: lower RMS values reflect greater accuracy.*

4.4.5 Family-wise Error

Analyses comprised a 2×2 repeated measures ANOVA (SD) (two main effects, one interaction effect) and two Wilcoxon signed-rank tests (RMS), yielding five statistical tests and one significant result (main effect of visual feedback) giving a percentage error rate of approximately 23%.

4.5 Discussion

This study investigated the effects of local muscle fatigue on shoulder internal rotation torque steadiness and matching accuracy under both visual and no-visual feedback conditions. The results did not support the hypothesis that local muscular fatigue would reduce measures of shoulder torque control as torque steadiness (SD) and torque matching accuracy (RMS) were not significantly different following the fatiguing protocol. The lack of change observed in torque matching accuracy supports the findings of Coskun et al. (2018), who found no significant effect of fatigue on shoulder internal rotation torque matching accuracy (50% MVC target torque) in a cohort of young healthy males, using a similar testing position.

We did demonstrate a significant main effect for visual feedback with lower SD (steadier torque) with visual feedback present, confirming findings for young healthy adults in previous studies (Tracy, 2007; Tracy, Dinunno, et al., 2007; Welsh et al., 2007). Our findings, however, are contrary to those of Baweja et al. (2009) and Slifkin et al. (2000) who demonstrated that *removal* of visual feedback resulted in increased steadiness of torque. Other studies have reported no effect of visual feedback condition on steadiness (Baweja et al., 2010; Christou et al., 2004; Kennedy & Christou, 2011; Vaillancourt & Russell, 2002). Methodological issues that could account for the differential findings include controlling for visual gain, and the amount of visual feedback prior to its' removal. The present study controlled for gain, and had an extended duration of visual feedback available to participants prior to the no visual feedback condition. This suggests that when sufficient visual feedback is provided before its removal, the CNS can establish reliable internal representations for torque production, leading to improved steadiness even without ongoing visual input.

The absence of fatigue effects on torque accuracy and steadiness is surprising given that fatigue-induced effects on torque steadiness have been consistently demonstrated at other joints (see Pethick & Tallent [2022] for review), with some studies also showing impaired torque matching accuracy (Vuillerme & Boisgontier, 2008; Wright & Arnold, 2012). Previous studies employing a comparable fatigue task to the current study (Ansdell et al., 2017; Pethick et al., 2015, 2018), have consistently demonstrated decreases in torque steadiness in the knee extensors.

Previous research has found that fatigue is dependent on a critical torque (CT) threshold, with tasks above the CT inducing greater metabolic declines and an onset of peripheral fatigue up to five times faster than below the CT (Burnley, 2009). This is thought to reflect the progressive recruitment of higher-threshold motor units to maintain torque output as lower-threshold units fatigue, accelerating the

accumulation of metabolites such as inorganic phosphate and hydrogen ions that impair cross-bridge cycling and excitation-contraction coupling (Allen et al., 2008). Furthermore, Pethick et al. (2015) found that, with an intermittent fatiguing protocol below the CT, no significant differences in torque steadiness measures were observed, in contrast with a protocol above the CT, likely reflecting this differential motor unit recruitment. For the present study, the CT for shoulder internal rotation was unknown. However, it seems likely that our 60% MVC target during the fatigue protocol would have been sufficiently above the CT to engage these mechanisms, and the changes in MVC and Borg scores support this interpretation. We demonstrated a mean 30% reduction in MVC comparable to other intermittent protocols at the shoulder (Iridiastadi & Nussbaum, 2006; Looft & Frey-Law, 2020), elbow flexors (Allman & Rice, 2001) and knee extensors (Pethick et al., 2016). Furthermore, near-maximal effort reported at task failure (Modified Borg $m=9.7$) and MVC remaining depressed following the post-fatigue matching task, confirmed that fatigue had not fully resolved and that early recovery was not a confounding factor.

The intermittent submaximal isometric fatiguing protocol was selected over a sustained contraction protocol as it more closely approximates the cyclical patterns of muscle activation observed during functional upper limb tasks and, in doing so, addresses two related concerns that have been raised about sustained protocols in the literature. First, sustained isometric contractions have been considered to lack ecological validity, with recent work suggesting that differences in observed fatigue effects between sustained and intermittent contractions may reflect differences in muscle physiological and biomechanical elements (including intramuscular pressure, temperature, and stiffness) elicited by each contraction type (Kavanagh et al., 2020; Madeleine et al., 2002). Second, the prolonged vascular occlusion that accompanies sustained isometric contractions may exaggerate metabolite-mediated peripheral fatigue (Pethick & Tallent, 2022), an effect that is not typical of real-world fatigue

induced by low-duration intermittent muscle activity in sport (McPhee et al., 2014; Pethick & Tallent, 2022). The intermittent design of the present protocol allowed for muscle reperfusion between contractions, reducing this confound. Earlier work at the lower leg (Löscher et al., 1994, 1996) and quadriceps (Kiyama et al., 2014) has shown decreased torque matching accuracy following fatigue induced by sustained or long-duration contractions, and it is plausible that the absence of such effects in the present study partly reflects these protocol differences.

Beyond protocol differences, a further possible explanation for the null fatigue effects relates to the time required to reach task failure and the associated metabolic accumulation. The mechanistic pathway outlined above is likely to be dose-dependent on the magnitude and duration of metabolic disturbance. In the study by Pethick et al. (2019), task failure occurred after $M \pm SD$ 11.5 ± 5.2 mins compared to 2.96 ± 1.05 minutes in the present study. Pethick et al. found a correlation between torque steadiness at 40% MVC and muscle metabolic rate measured via muscle oxygen consumption (mVO_2), such that as mVO_2 increased, torque steadiness decreased. Specifically, local muscular fatigue-induced metabolic changes are thought to increase small diameter (Group III & IV) nociceptive muscle afferent input, which leads to motor neuron inhibition via central projections (Amann et al., 2015), necessitating an increase in voluntary drive and motor unit recruitment to maintain torque output and, in turn, increasing common synaptic input and torque fluctuations (Enoka & Farina, 2021; Farina & Negro, 2015; Kennedy et al., 2013). Conceivably, the relatively rapid onset of fatigue in the present study did not induce sufficient metabolic-mediated peripheral fatigue and Group III and IV afferent input to significantly affect torque steadiness via this mechanism.

A fourth consideration for the lack of effect of fatigue on torque control in the present study relates to the relatively low target torque value used. The fatiguing protocol adopted may have resulted in larger motor units being relatively more fatigued

compared to somewhat fatigue-resistant smaller motor units. Hence, for the torque control task at a target of 35% MVC, smaller motor unit recruitment may have been sufficient for individuals to maintain torque matching accuracy and steadiness.

Supporting this interpretation, previous work employing an intermittent isometric fatigue protocol at the quadriceps muscle (Ansdell et al., 2017) demonstrated reduced torque steadiness post-fatigue, but only for a 50% MVC target, and not at 30% MVC. Future studies may wish to examine whether fatigue affects torque control using target torques at a higher percentage of MVC, or with lower intensity, longer duration intermittent duty-cycled fatigue protocols.

This study incorporated both visual and no-visual feedback conditions to elucidate whether fatigue impairs proprioceptive inputs for torque control, and whether the CNS compensates by increasing reliance on visual feedback to maintain performance. Sensorimotor integration is thought to involve the weighting of sensory inputs based on their reliability and variability, with more reliable signals receiving greater weighting in motor control. Visual feedback typically demonstrates higher precision and therefore dominates motor control mechanisms when present (Smeets et al., 2006). However, removing visual feedback shifts the weighting toward proprioceptive and force-sense inputs. If fatigue degrades the quality of proprioceptive sensory information, introducing noise that makes afferent signals less reliable, the CNS may re-weight toward visual feedback to maintain performance (Tagliabue & McIntyre, 2014). Consequently, removing visual feedback under fatigued conditions should reveal whether fatigue has compromised proprioceptive pathways, as participants would be unable to compensate for degraded proprioceptive input.

The absence of a significant effect of fatigue in the no visual feedback condition suggests that fatigue did not differentially impair proprioceptive sources of feedback in healthy participants. If fatigue had significantly degraded proprioceptive acuity, we

would have expected a greater decrement in torque RMS error during the no-visual feedback condition compared to the visual feedback condition. Instead, the similar pattern of non-significant fatigue small effects across both feedback conditions (VFB $r=-0.13$; NVFB $r=-0.11$) indicates that proprioceptive pathways remained sufficiently intact to support accurate and steady shoulder internal rotation torque production.

Whilst neither measure reached statistical significance, the pattern of effect sizes offers tentative support for the hypothesis that fatigue would have a greater impact on steadiness than accuracy. The effect size for changes in SD was medium-to-large ($\eta_p^2=0.11$), whereas for RMS the effects were small ($r=-0.11$ to -0.13). Whilst different effect size metrics are not directly comparable, the differences suggest that had the study been adequately powered, fatigue effects on steadiness may have been more readily detected than effects on accuracy, consistent with findings at other joints (Pethick et al., 2016). It should be noted, however, that because RMS data required non-parametric analysis, a formal statistical comparison of the fatigue effect between the two measures was not possible.

This was the first investigation of fatigue effects on shoulder torque steadiness, addressing an important gap in the literature given the established role of fatigue as a risk factor for shoulder injury in overhead activities (Schwank et al., 2022). The study had several methodological strengths.

First, we employed comprehensive fatigue confirmation through both objective (MVC decrement) and subjective (modified Borg RPE scale) measures assessed immediately post-fatigue and following the experimental protocol. This dual approach provided confidence that participants remained in a sufficiently fatigued state throughout testing. This addresses a key concern in fatigue research that recovery of muscle force production during post-fatigue protocols may attenuate observed fatigue-induced effects (Place & Millet, 2020).

Second, the inclusion of both visual and no-visual feedback conditions enabled examination of the relative contributions of visual and proprioceptive sensory inputs to shoulder torque control, and whether fatigue differentially affects these sensorimotor pathways. This design allowed for assessment of whether visual feedback could compensate for potential fatigue-induced degradation of proprioceptive function.

However, there were also several study limitations that should be taken in account. First, a within-subjects, repeated measures design was utilised, with no control group. Due to the fixed order of testing, a control group could have indicated whether practice effects may have been present, that may have obscured any decrement in torque control with fatigue. We chose a repeated measures design as it was unclear what a sufficient washout period may be after inducing muscle fatigue, and we wanted to minimise both participant burden and dropout rates by limiting the number and duration of data collection sessions, particularly given the uncertainty around restriction with the Covid-19 epidemic.

Second, we also chose to focus on the shoulder internal rotators in a position approximating the 'apprehension position' for the shoulder as we felt that this reflected a position of clinical relevance to both shoulder function and injury risk (Asker et al., 2018; Labriola et al., 2005), with the internal rotators acting as the main active stabilisers of humeral head translation in this position (Day et al., 2012; Huxel et al., 2008; Myers et al., 2003). The results may be different in other positions where the joint is in mid-range, or if other muscle groups were tested. Examining the effects of fatigue on torque control of other muscles, such as the posterior cuff muscles, and in different positions would therefore be of further benefit.

Third, our sample size ($n=20$) may have limited statistical power, increasing the chance of Type II error. Although the main effect of fatigue did not reach statistical

significance, the effect size for change in SD was medium-to-large ($\eta_p^2=.11$) suggesting the study may have been underpowered to detect this effect. For accuracy the effect size was very small (VFB $r=-0.13$; no VFB $r=-0.11$) suggesting that detecting meaningful changes would be challenging even with substantially larger sample sizes. However, MDC_{GROUP} analysis provides an additional perspective. The observed pre- to post-fatigue difference for SD of 0.04 Nm exceeded the MDC_{GROUP} threshold of 0.02 Nm by a factor of 2, consistent with the medium-to-large effect size and supporting the interpretation that the study may have been underpowered to detect a genuine fatigue effect on steadiness. For accuracy, the observed RMS difference of 0.03 Nm also exceeded the MDC_{GROUP} of 0.01 Nm, though the very small effect size suggests this should be interpreted cautiously. For the no visual feedback condition, initial pilot testing did not include a no visual feedback condition. As such, the observed differences in this condition should be interpreted with additional caution as the measurement precision remains uncertain. A further consideration is that pilot data used to inform the a priori power calculations were collected under the control condition only. It is possible that fatigue conditions introduced additional performance variability, which would alter the precision of the effect size estimates. Furthermore, without established test-retest reliability for post-fatigue torque measurements, variability in fatigue depth across trials may have inflated measurement error and reduced sensitivity to real differences, compounding the underpowering concern noted above.

This raises an important interpretive question - does this finding represent a true minimal influence of fatigue on torque matching accuracy in healthy young adults, or do the measures lack sensitivity to detect small but potentially meaningful changes? Whether the observed RMS difference reflects a genuine effect or measurement variability remains unclear; previous studies in the lower limb with similar or smaller sample sizes have demonstrated significant effects of intermittent submaximal

isometric fatigue protocols on knee extensor torque RMS error (Pethick et al., 2016), suggesting that the current study may have lacked sufficient power rather than that fatigue genuinely has no effect on accuracy.

Fourth, the ecological validity of the fatigue protocol requires consideration. Whilst an intermittent duty cycle fatigue protocol offers advantages over a sustained contraction protocol, it remains somewhat contrived in that it involves highly controlled torque production in a single plane across one joint. This contrasts with typical upper limb movement occurring across different planes across multiple joints simultaneously. Previous studies (Dupuis et al., 2021, 2022; Ebaugh et al., 2006a) have addressed this by using a fatigue protocol consisting of cycled tasks (small object manipulation and weighted arm elevations), until a predetermined level of exertion on a Borg scale was reached. Whilst this has arguably better ecological validity, it is difficult to determine whether muscles of interest are truly fatigued without objective measures such as MVC. Furthermore, these studies reported time to fatigue ranging from a mean of 6.5 to 10.7 mins, which may introduce confounding factors beyond neuromuscular fatigue itself, such as declining motivation and attention over prolonged efforts (Neyroud et al., 2012; Souron et al., 2020). Another consideration is that a more challenging or real-world representative fatiguing protocol may have yielded different results. A previous study (Tripp et al., 2007) demonstrated that a functional fatiguing protocol in baseball players (using a repeated throwing task) led to increases in multi-joint angle reproduction errors compared to a non-fatigued state. However, such a fatiguing protocol would be difficult to standardise across participants with quite different activity levels and sports played.

Fifth, the absence of electromyographic (EMG) recordings, which would have provided mechanistic insight into the neuromuscular adaptations occurring under fatigue. Frequency-domain analysis of both EMG signals (Merletti et al., 1991) and

torque output would have been valuable. EMG spectral shifts derived from (e.g. declining median frequency) surface EMG provide sensitive markers of declining conduction velocity and motor unit recruitment adaptations characteristic of muscle fatigue (Enoka & Duchateau, 2008; McDonald et al., 2019; Minning et al., 2007). However, this would only be possible for superficial muscles at the shoulder where cross talk is a potential problem (Kamen & Caldwell, 1996). Deeper muscles require fine wire electrodes introduces sampling bias as electrical activity is recorded from only a limited number of motor units from a small portion of muscle (Besomi et al., 2019). Frequency analysis of the torque signal itself would have distinguished whether maintained torque control reflected adaptive motor unit substitution or compensatory synergist recruitment as these mechanisms produce distinct spectral signatures (Contessa et al., 2016; Kouzaki et al., 2004; Shinohara et al., 2009). Such analyses could have clarified whether the maintenance of torque control observed in our healthy cohort reflected adaptive motor unit recruitment strategies, compensatory activation of less-fatigued synergist muscles, or altered antagonist co-contraction patterns.

However, our primary interest was the shoulder internal rotators, particularly the subscapularis as a main anterior stabiliser in the testing position (Day et al., 2012; Huxel et al., 2008; Lee et al., 2000). Given the deep anatomical location of the subscapularis, surface EMG is not feasible (Motabar et al., 2019; Waite et al., 2010). While fine-wire intramuscular EMG is possible, it introduces methodological challenges including participant discomfort, difficulty ensuring correct electrode placement within the target muscle, and potential alteration of motor control strategies due to needle insertion (Kadaba et al., 1992; Waite et al., 2010). Future investigations examining accessible shoulder muscle groups via surface EMG (e.g., infraspinatus, deltoid, trapezius) could elucidate neuromuscular strategies and identify whether certain muscles exhibit preferential fatigue (McDonald et al., 2019),

informing targeted injury prevention and rehabilitation interventions for populations exposed to high-volume overhead workloads.

Finally, as discussed in more detail in Chapter 3 (Section 3.5) the absence of hormonal cycle control for female participants is a limitation of the current study. The effect of hormonal status on fatiguability is inconsistent across the literature. A recent review (Pereira et al., 2020) highlighted conflicting results across studies, with differing hormonal cycle stages influencing time to task failure during isometric contractions and the direction of changes on fatigue perception (RPE), while others found no significant effects. Future research should control for menstrual cycle phase and hormonal contraceptive use to clarify whether hormonal status influences shoulder torque control under fatigue.

Additional limitations regarding single target torque use, testing position and participant characteristics (shoulder injury history and physical activity levels) are discussed in Chapter 3 (Section 3.5) and apply equally to the current study.

4.6 Conclusion & Future Research Directions

Isometric shoulder internal rotation torque steadiness and torque matching accuracy variables were not significantly affected following a protocol of fatiguing intermittent isometric contractions. There was a main effect for visual feedback but no interaction effect with fatigue was observed. Several potential explanations for these findings have been discussed. However, the null findings of fatigue effect can be viewed positively, as it suggests that in a limb position where injuries often occur, and at a muscle activity level typical in many sporting and work movements, torque control may not be substantially affected.

Several key directions for future research emerge from this study. Establishing shoulder-specific critical torque thresholds would enable standardised fatiguing protocols and facilitate cross-study comparison. Investigating dynamic tracking tasks

and higher post-fatigue target torques ($\geq 50\%$ MVC) would determine whether the current study's static protocol and relatively low target torque limited sensitivity to detect fatigue effects. Extending research to clinical populations such as individuals with rotator cuff pathology, shoulder instability, or those most susceptible to shoulder injury (e.g., overhead athletes), would provide translational insights informing rehabilitation progression, return-to-sport criteria, and injury prevention strategies by revealing whether injured or at-risk populations demonstrate different fatigue responses to those observed in the current study. Furthermore, comparing isometric versus functional sport-specific fatiguing protocols would clarify whether laboratory findings translate to real-world athletic and occupational contexts, specifically, whether these approaches elicit comparable fatigue magnitudes and engage similar neuromuscular mechanisms. If isometric and functional protocols produce divergent fatigue responses, this would question the validity of extrapolating laboratory-derived conclusions to applied settings, and highlight the need for more ecologically representative methodologies in fatigue research.

Finally, incorporating frequency-domain analysis of the torque-time curves would provide additional insights beyond the magnitude-based variables (SD and RMS) employed in the current study. Frequency-domain analysis enables examination of specific frequency bands elucidating which control mechanisms are affected by fatigue (Y. T. Lin et al., 2014; Vaillancourt & Newell, 2003). For example, fatigue-induced increases in higher-frequency components may reflect altered motor unit recruitment patterns or increased physiological tremor. Additionally, time-domain complexity measures, such as Sample Entropy, could reveal fatigue effects on the complexity of torque and how this may change in the presence of fatigue, providing insights into the adaptability of the sensorimotor system (Clark et al., 2023). These analytical approaches would complement traditional variability measures and

enhance mechanistic understanding of fatigue effects on shoulder sensorimotor control.

Chapter 5: The Effect of Shoulder Taping on Submaximal Torque Control at the Shoulder

5.1 Introduction

After injury, sensorimotor deficits have been consistently demonstrated with measures such as joint position sense (JPS) (Fyhr et al., 2015; Gumina et al., 2019) and torque control (Pethick, Clark, et al., 2022) detrimentally affected. Taping is purported to improve sensorimotor control and prevent reinjury, with varying mechanisms including mechanical effects such as changing joint ROM (McConnell et al., 2012); muscle performance effects such as altered muscle activation timing (Snodgrass et al., 2018); psychological effects such as boosting confidence (Delahunt et al., 2010); and/or effects on proprioceptive acuity (Clark et al., 2015). Whether such effects are found in those individuals without injuries is less clear (Ager et al., 2023; Ghai et al., 2023), although taping is often used prophylactically.

Taping is proposed to influence sensorimotor control primarily through augmented afferent feedback from cutaneous mechanoreceptors. The theoretical basis centres on increased afferent information arising from tactile stimulation (Konishi, 2013; Morrissey, 2000) and a 'skin stretch' effect during movement (L. A. Kelly et al., 2010). This heightened input is posited to increase motor cortex excitability and reduce motor neuron thresholds, facilitating easier recruitment of motor units (Alexander et al., 2003; Callaghan et al., 2012; Dehghan et al., 2024). Through this sensorimotor pathway, tape application may theoretically influence not only torque magnitude but also the timing, accuracy, and steadiness of torque output. By providing enhanced afferent feedback during muscle contraction, taping could improve the precision of motor unit recruitment and modulation, key parameters underlying torque control.

Evidence from other joints supports the notion that tape effects extend beyond mechanical restriction. Rigid ankle tape restrains inversion through mechanical

mechanisms (movement deceleration) and afferent input to the central nervous system (Briem et al., 2011). The direction of tape application may also be influential; Alexander et al. (2008) found that rigid tape applied along muscle fibres reduced gastrocnemius H-reflex amplitude, whereas application across the muscle belly did not. These findings suggest that taping can modulate spinal reflex pathways, potentially influencing motor unit regulation and sensory integration that underpin torque control.

Taping could theoretically improve torque control by optimising muscle activation patterns, including reducing excessive co-contraction or improving the timing and efficiency of agonist activation. However, evidence for the influence of taping on muscle activation is inconsistent. A systematic review concluded that kinesiology taping does not affect maximal muscle strength measures (Csapo & Alegre, 2015), though these studies examined peak torque rather than submaximal torque control parameters such as steadiness or accuracy, which may be more sensitive to proprioceptive interventions. At the shoulder, while some studies report changes in trapezius muscle activation timing during shoulder abduction (Snodgrass et al., 2018) and increased acromiohumeral distance potentially due to altered muscle force production (Martín-San Agustín et al., 2021), others observed no EMG effects on shoulder muscles (Cools et al., 2002). Bidirectional EMG changes in the rotator cuff (Stoller, 2013) and variable outcomes on periscapular muscle activity (Yildiz et al., 2020) suggest that if taping does influence torque control, it may do so through complex alterations in agonist-antagonist coordination rather than simple changes in muscle activation amplitude.

If taping increases afferent input to the CNS, it could theoretically improve motor response time to perturbations, thereby enhancing dynamic torque control during tasks requiring rapid adjustments. Whilst no studies have explored this at the shoulder, at the ankle rigid taping has been shown to increase peroneal EMG activity

compared to kinesiology tape and no tape (Briem et al., 2011) and to decrease peroneal response time in unstable ankles following inversion perturbation (Karlsson & Andreasson, 1992). Similarly, taping led to greater peroneal activation per degree of inversion during simulated sprain compared to no-taping (Lohrer et al., 1999). Conversely, neither elastic nor rigid tape affected peroneus longus EMG latency during inversion perturbations (Trégouët et al., 2013), and rigid taping actually delayed the peroneal latency reflex in response to sudden inversion regardless of ankle injury status (Shima et al., 2005). Such inconsistencies suggest that the relationship between taping and neuromuscular response may depend on joint architecture, tape type, and the nature of the perturbation - factors that remain insufficiently explored.

Regarding studies that have investigated the effect of taping on proprioception, the majority have explored joint position sense (JPS) or kinaesthetic measures of proprioceptive acuity. At the shoulder, a recent review (Ager et al., 2023) on the proprioceptive effect of kinesiology taping found that taping had mixed effects on JPS in healthy populations, with two studies finding some improvement in JPS (Burfeind & Chimera, 2015; J. J. Lin et al., 2011) and two studies finding no significant improvement (Aarseth et al., 2015; Zanca et al., 2015). Positive effects for using rigid taping on JPS are also questionable, with studies of uninjured Australian Football (AFL) players (Bradley et al., 2009) and healthy cricket fast bowlers (Weerakkody & Allen, 2017) finding no significant effect of rigid taping for GHJ support on active limb repositioning tasks. However, in the latter study, taping did appear to reduce JPS errors following a fatiguing task (Weerakkody & Allen, 2017). While these JPS findings suggest taping may have some proprioceptive effect at the shoulder, they do not address whether taping influences the torque-related aspects of sensorimotor control.

In summary, taping may influence torque control through several potential mechanisms: 1) enhanced proprioceptive feedback from cutaneous mechanoreceptors, which could improve the precision of torque matching and steadiness; 2) altered muscle activation patterns, which may optimise motor unit recruitment and agonist-antagonist coordination for submaximal contractions; and 3) improved motor response timing, which could enhance performance during dynamic tasks requiring rapid torque adjustments. However, evidence for each mechanism remains inconsistent, and no studies have directly examined these effects on shoulder torque control.

Concerning sense of force, a recent systematic review and meta-analysis (Ghai et al., 2023) concluded that kinesiology and elastic tapes significantly improved absolute torque matching accuracy across joints, whereas rigid tape did not. This review included 11 studies using static target-matching tasks, of which 9 used kinesiology tape, and two used rigid tape. Six studies explored taping effects at the wrist and five investigated effects at the ankle; no studies have investigated taping effects on torque control at the shoulder. Furthermore, these studies assessed only matching accuracy; none examined torque steadiness. All studies used static matching paradigms; no dynamic tracking tasks were included.

Despite widespread use of rigid taping at the shoulder, significant gaps remain in understanding its effects on torque control. While taping has shown inconsistent effects on JPS and muscle activation, no research has specifically explored its influence on torque steadiness or accuracy at the shoulder. Furthermore, existing torque control studies have used only static matching tasks; investigating more functionally representative dynamic tracking tasks may provide important insights for injury prevention and rehabilitation (Ward et al., 2019).

Importantly, vision provides dominant sensory information for motor control, potentially masking proprioceptive contributions from taping. Of the studies in the

Ghai et al. (2023) review, all used a torque matching task that involved visual feedback followed by removal of the visual feedback. The dependent variables from the no-visual feedback task were used for data analysis, but none compared taping effects on torque control across visual conditions. Examining torque control under both eyes-open and eyes-closed conditions allows isolation of the proprioceptive effects of taping; if taping works through proprioceptive mechanisms, effects should be more pronounced when visual feedback is removed.

5.1.1 Aims

The aims of this study were therefore to investigate the effect of a commonly applied shoulder rigid taping technique on shoulder isometric torque control of the internal and external rotators in a healthy population. We hypothesised that taping would: 1) improve static torque matching steadiness (decreased SD) and accuracy (decreased RMS) to a greater extent in the absence of visual feedback compared to with visual feedback; 2) lead to greater improvements in external than internal rotation, as tape restricting external rotation should increase cutaneous afferent input during that task; and 3) improve accuracy more during torque tracking than static torque matching with visual feedback, given the tracking task's greater complexity.

5.2 Methodological Considerations

5.2.1 Common Methodologies

The methodological considerations for the common aspects of the torque control tasks are discussed in Chapter 3: isometric peak torque (Section 3.2.1, p.95); task selection (Section 3.2.2, p.96); target torque levels (Section 3.2.3, p.97); testing position (Section 3.2.4, p.98), limb dominance (Section 3.2.5, p.99); cutaneous sensory influence (Section 3.2.6, p.100); visual gain (Section 3.2.7, p.101); and learning effect (Section 3.2.8, p.102). The methodological considerations unique to this chapter are discussed in detail below. Chapter 4 presents the rationale for visual feedback condition (Section 4.2.2 pp. 145) in depth, briefly, multisensory integration

theory suggests the CNS shifts reliance between visual and proprioceptive inputs depending on availability and reliability of sensory information. In this study comparing visual and no-visual feedback conditions therefore allows for examination whether removal of visual feedback reveals proprioceptive contributions from taping that might otherwise be masked under the visual feedback condition. The methodological considerations unique to this chapter are discussed in detail below.

5.2.2 Rigid vs elastic tape

With an aim to prevent injury, strapping with rigid tape is a longstanding technique used by physiotherapists and athletic trainers. It is a woven, high adhesive tape with a low elastic modulus typically used to enhance joint stability by restricting undesirable joint movement and enhancing proprioception (Bradley et al., 2009). Despite its longstanding and widespread clinical application, research into the effectiveness of rigid tape at the shoulder remains limited to only two studies (Bradley et al., 2009; Weerakkody & Allen, 2017), with both studies finding no effect of taping on JPS acuity in healthy Australian Football League (AFL) and cricket players respectively.

The early 2010s saw a proliferation of the use of kinesiology tape (S. Williams et al., 2012), a thin woven tape with a high elastic modulus. Amongst many claimed mechanisms of effect is the improvement of sensorimotor control (de Oliveira et al., 2019). However, despite a significant rise in its popularity, evidence is lacking for its efficacy or to support its use in the prevention of sports injuries (S. Williams et al., 2012), or the treatment of shoulder disorders (Celik et al., 2020) and rotator cuff tendinopathy (Desjardins-Charbonneau et al., 2015). A recent systematic review and synthesis of the literature of the effects of kinesiology taping on shoulder proprioception, (Ager et al., 2023) found little to no effect on proprioception with only low certainty evidence for an effect on JPS in healthy individuals (4 studies, n=79) and very low certainty of an effect on in those with shoulder injury (2 studies, n=52).

5.2.3 Taping technique

Common rigid taping techniques at the shoulder are varied, depending on intended effect (Bradley et al., 2009; Kneeshaw, 2002; Morrissey, 2000). For example, several techniques are suggested to assist with scapula positioning (for example, see Figure 17) with small but significant changes to muscle activation timing (Snodgrass et al., 2018) and scapula kinematics (Leong et al., 2017; Ozer et al., 2018). However, the link between scapula kinematics and shoulder injury/pain remains questionable (McQuade et al., 2016), with altered scapula kinematics (dyskinesia) not an independent risk factor for shoulder injury amongst athletic populations (Hogan et al., 2021). Furthermore, several of the taping techniques involve a limited number of rigid tape or kinesiology tape strips running from the GHJ to the scapula, with questionable biological plausibility for effect, and in the case of kinesiology taping, demonstrated limited efficacy in the management of shoulder disorders (Celik et al., 2020; Desjardins-Charbonneau et al., 2015).

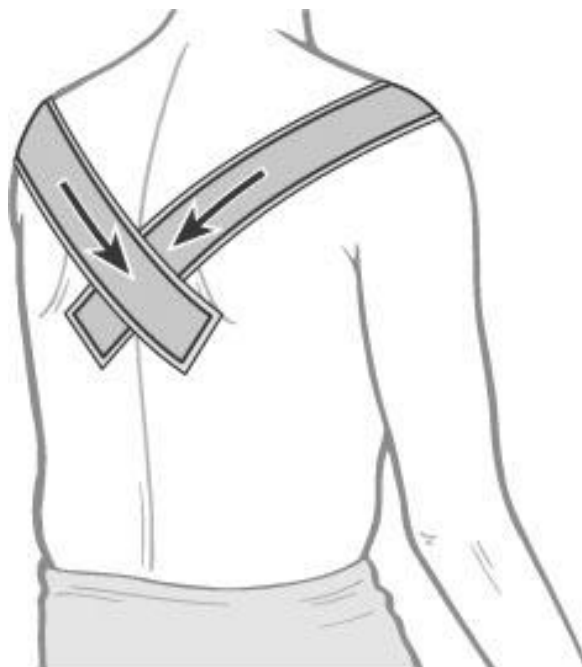


Figure 17. An example of taping for scapula position [*taken from Kneeshaw (2002) with permission*]

A common pattern of taping using rigid tape involves the overlapping of strips of tape from a mid-humeral anchor to a strip over the top of the shoulder (see Figure 18).

This technique aims to improve GHJ stability by limiting excessive GHJ movement into the abducted and externally rotated (apprehension) position. This pattern, or variations of it, are seen frequently in contact sports such as rugby and AFL as well as overhead sports such as volleyball, tennis and throwing sports. Despite being a widely used technique, only two studies (Bradley et al., 2009; Weerakkody & Allen, 2017) have studied the effects of this taping application, with their findings demonstrating no effect on shoulder JPS.



Figure 18. An example of taping for GHJ stability [taken from Bradley et al. (2009) with permission]

5.2.4 Use of a comparator

According to the ClinicalTrials.gov glossary, a sham comparator arm is "a group of participants receiving a procedure or device that appears to be the same as the actual procedure or device being studied but does not contain active processes or components" (U.S. National Library of Medicine, n.d.). In randomised controlled trials, sham conditions are valuable for controlling placebo effects and participant expectations, thereby isolating the specific therapeutic mechanisms of an intervention (Hróbjartsson & Gøtzsche, 2010). Such controls are most appropriate

when the sham can be designed to be truly inactive with respect to the proposed mechanisms of treatment, as sham interventions are assumed to be physiologically inert (Birch, 2006; Locher et al., 2018).

However, applying this standard to taping research presents a fundamental methodological challenge. One of the proposed mechanisms through which taping may exert its effects is proprioceptive enhancement via stimulation of cutaneous mechanoreceptors (Ghai et al., 2023). Any tape adhered to the skin, regardless of tension, application technique, or material, will inevitably stimulate these receptors through contact with the epidermis (Cupler et al., 2020). Consequently, sham tape cannot be considered a physiologically inert intervention when mechanoreceptor stimulation is a hypothesised mechanism, as the sham condition would share this proposed 'active process' with the experimental condition.

A three-condition design including taping, sham taping, and no-taping would theoretically provide greater mechanistic insight by enabling comparison of: a) the specific effects of taping technique beyond cutaneous stimulation (taping versus sham), and b) the combined effects of taping including any mechanoreceptor-mediated contributions (taping versus no-tape). However, such designs substantially increase participant burden through additional testing sessions, which was a particular concern given data collection constraints during the COVID-19 pandemic (see Introduction to Experimental Chapters, p.14).

Given these considerations, the present study employed a randomised crossover design comparing taped and untaped conditions. This approach addresses the clinically and pragmatically relevant question of whether taping produces any measurable effect through any mechanism, including placebo, expectation, and physiological pathways. This also reflects the clinically relevant comparison facing clinicians and athletes in applied settings: whether taping produces any meaningful

effect compared with no taping. Should taping effects be established, subsequent research employing sham conditions could then investigate which specific mechanisms contribute to any observed effects.

5.2.5 Washout Period

The proposed mechanisms of rigid taping include mechanical restriction and proprioceptive enhancement (Kneeshaw, 2002; Morrissey, 2000), the latter dependent on cutaneous mechanoreceptor stimulation. There is no biological plausibility for these effects to persist beyond tape removal. Cutaneous mechanoreceptive afferents recover from adaptation along exponential time-courses, with recovery time constants in the order of seconds: approximately 9–17 seconds for slowly adapting type I afferents and 21–30 seconds for rapidly adapting and Pacinian afferents (Leung et al., 2005). These recovery dynamics indicate that any taping-induced modulation of mechanoreceptor discharge would dissipate within seconds of tape removal. Consistent with this, Alexander et al. (2003) found that taping-induced inhibition of lower trapezius H-reflex amplitude was not sustained after tape removal, and no study has demonstrated sensorimotor effects enduring beyond the removal of tape. Indeed, even immediate mechanical and neuromuscular effects during tape application remain unsubstantiated (Leibbrandt & Louw, 2015).

Crossover designs in taping research have employed variable washout periods, from unreported intervals within a single session (Bradley et al., 2009; Cools et al., 2002; Shaheen et al., 2015) to 5–10 minutes (W.-H. Lee et al., 2011; Z.-M. Lin et al., 2021; McConnell et al., 2012). Given the known physiology of cutaneous mechanoreceptor recovery and precedent from previous literature employing shorter washout periods, a 15-minute washout was conservatively chosen for this study. A 15-minute washout period, coupled with randomised allocation to condition order, minimises the risk of carryover effects whilst reducing participant burden.

5.2.6 Summary

Numerous techniques using different taping types are used in clinical practice with various goals of taping application, with proprioceptive enhancement being a commonly claimed mechanism. Much of the current research to date has focused on elastic kinesiology taping, with limited evidence for its effectiveness or efficacy. Amongst sports with an inherent higher risk of shoulder injury, such as contact and throwing sports, taping using rigid tape to provide GHJ stability remains commonplace; however, this tape type is under-investigated, and in need of further exploration given its widespread use. In particular, given the claims of enhancing proprioception, investigating torque control measures is paramount given the limited research has been primarily focused on JPS, and no studies investigating the effect of taping on any torque control metrics at the shoulder.

5.3 Methods

5.3.1 Study Design

A randomised crossover trial experimental design was used in a cohort of healthy young adults. A crossover design was used as it is more efficient (i.e. it requires a smaller sample size due to a reduction in variance), and we did not expect any carryover effects once the tape had been removed. A washout period of 15 minutes was used between taping and no taping conditions. Data for this study was collected concurrently with the study described in Chapter 3, with the taping and no-taping conditions being investigated first.

5.3.2 Ethical Approval

Ethical approval was provided by the New Zealand Health and Disability Ethics Committees (HDEC) (reference 21/NTB/98) and Auckland University of Technology Ethics Committee (AUTEK) (reference 21/348).

5.3.3 Sample Size Calculation

Sample size calculations were performed in G*Power v3.1.9.6 (Faul et al., 2007). As existing literature did not provide sufficiently comparable data to inform our sample size calculation, pilot testing (n=6; 3M:3F, age range 20-28) was conducted prior to data collection to establish means and SDs, using the test procedures described in Sections 3.3.10 and 3.3.11. The variables of interest were: torque steadiness (SD) and accuracy (RMS error) during torque matching with visual feedback; and accuracy (RMS error) during torque tracking. Pilot participant data were not included in the main study.

For torque matching, the mean (\pm SD) for steadiness and accuracy were 0.32 ± 0.14 Nm and 0.35 ± 0.17 Nm respectively. For torque tracking, the mean (\pm SD) for accuracy was 2.37 ± 0.54 Nm. In the absence of established minimally clinically important difference (MCID) values for torque steadiness and accuracy, a 25% change was selected as the target threshold based on effect sizes reported for taping effects on torque accuracy in healthy populations compared to no taping (Hedges' $g = -0.53$; Ghai et al., 2023). Using our pilot data for accuracy (mean 0.35 ± 0.17 Nm), a 25% change corresponds to an expected difference of 0.0875 Nm, yielding Cohen's $d = 0.51$, which is consistent with the meta-analytic results of (Ghai et al., 2023) and indicating our sample size targets an empirically supported magnitude of change.

All sample size calculations employed two-tailed tests, with an α level of 0.05, power of 80%, and an estimated correlation between repeated measures of $r=0.7$. As shoulder torque control tasks differ in complexity and attentional demand, to detect a more conservative 25% difference in the variables of interest between taped and untaped conditions (matched pairs), sample size calculations yielded n=20 for torque matching RMS, n=17 for torque matching SD, and n=7 for tracking RMS. The largest required sample (n=20) was used to determine the recruitment target. To account for

a maximum dropout rate of 10%, the recruitment target was set at 22. A 25% change corresponds to an absolute between condition difference of 0.09 for torque matching RMS ($d=0.51$), 0.08 for torque matching SD ($d=0.57$) and 0.59 for tracking RMS ($d=1.10$). Pilot testing in the same cohort ($n=6$) established excellent test-retest reliability for torque RMS ICC=0.99, 95%CI [0.92,1.00], SEM=0.02, torque SD ICC=0.95, 95%CI [0.66,1.00], SEM=0.03, and for tracking RMS ICC=0.95, 95%CI [0.87,0.99], SEM=0.12. Using these values, the minimum detectable change for the group differences (MDC_{GROUP}) was calculated as 0.01 for RMS and 0.02 for SD for the torque matching task, and 0.07 for RMS for the torque tracking task ($MDC_{GROUP} = (SEM \times 1.96 \times \sqrt{2}) / \sqrt{n}$, where $n = 20$). Importantly, the target between-condition differences used in the power calculations exceeded their respective MDC_{GROUP} values by factors of 9.0, 4.0, and 8.4 respectively, indicating that the measurement approach utilised possesses sufficient sensitivity to detect the minimum effects for which the study was powered.

5.3.4 Participant Recruitment

Twenty-one healthy volunteers were recruited via recruitment posters placed on university noticeboards and snowball sampling. A cohort of young adults was sought to represent a population unlikely to have significant underlying upper limb pathology and also represent individuals comparable with typical traumatic shoulder injury populations. Potential participants were screened for inclusion and exclusion criteria via phone conversation by the principal investigator. Those participants who met the inclusion and exclusion criteria were invited to participate via consecutive sampling. No participants had previously been involved in pilot testing. All participants provided written informed consent prior to commencement of data collection and were then considered enrolled in the study.

5.3.5 Inclusion/Exclusion Criteria

The following inclusion and exclusion criteria were applied:

Inclusion: Individuals aged 20-35 years, without history of shoulder injury. (criteria for shoulder injury were any shoulder or upper arm symptoms that had necessitated input from a health care professional).

Exclusion: Current or past upper limb or spinal pathology that required management by a health professional, history of a neurological condition, other forms of global joint pathology (e.g. hypermobility syndrome, arthropathies), known tape allergy, skin conditions that would preclude taping (e.g. psoriasis) and non-fluency in the English language.

Prior to data collection, participants were screened for shoulder ROM and the apprehension test (Tzannes & Murrell, 2002). This screening was performed by the principal investigator, a physiotherapist with over 20 years of clinical experience. All participants demonstrated sufficient GHJ ROM for the testing protocol (90° of abduction and 90° external rotation) and none demonstrated significant hypermobility (>180° of total rotation in 90° abduction (Nicholson & Chan, 2018)) or a positive shoulder apprehension test.

5.3.6 Participant Characteristics

A questionnaire created in REDCap (Research electronic data capture (Harris et al., 2009)) was used to collect participant characteristics such as age, height, weight, and ethnicity. Defining sports participation and expertise varies considerably in the literature, especially across sports (Swann et al., 2015). Therefore, sports participation was defined pragmatically (social=recreational e.g. friends and family; competitive = take part in organised league or events; elite = representative (e.g. region/national)). No participants participated in competitive or elite level overhead sports defined as 'a sport in which an athlete, with the forearm/hand lifted above the head, repetitively propels a ball or shuttle against an opponent or a teammate' (Asker et al., 2018).

5.3.7 Randomisation, Allocation Concealment and Blinding

After written informed consent was obtained, and before data collection, a research assistant (not involved in participant recruitment or screening) used a computer-generated randomisation schedule to allocate participants in a randomised counterbalanced way, to either a 'tape then no tape' sequence or vice versa (see Figure 20). The principal researcher remained blinded to taping allocation throughout data collection and analysis. The randomisation schedule was only revealed after all statistical analyses were completed. Due to the nature of the intervention, participants were not able to be blinded to taping status.

5.3.8 Experimental Set-up

The dominant shoulder was used as the test shoulder for all participants. Limb dominance was ascertained by asking which hand participants write with.

Participants were then positioned in the Biodex dynamometer (Biodex 3, Biodex Medical Systems, Shirley, NY, USA) with the GHJ positioned in 90° elevation in the scapula plane, 80° external rotation, and the elbow at 90° of flexion and aligned with the dynamometer (for more detail see Chapter 3, Section 3.2.4).

5.3.9 Warm-up and Shoulder Peak Torque

The previously described warm-up and peak torque procedures (Chapter 4, Section 4.2.8 and 4.2.9 respectively) were used. Briefly, after a standardised general shoulder warm-up, two 5-second submaximal contractions were performed at 25%, 50% and 75% perceived maximal effort. Three maximal effort contractions with verbal encouragement were then undertaken for GHJ internal rotation, and the greatest of those three efforts was taken as the participant's peak torque. A familiarisation with the equipment and the torque matching task was also part of the warm-up.

5.3.10 Torque Matching Task

The torque matching task previously described in Chapter 4 (Section 4.3.9) was used. In summary, participants were required to match a 35% MVC target torque for internal and external rotation. Tasks were performed in a randomised order, with visual feedback of the target torque and torque trace provided by a screen placed 1.5m away. When an indicator light switched on, participants generated an isometric contraction and tried to reach the target torque as quickly as possible and then hold as steadily as possible for a 10 second period. They then relaxed, the screen was covered, the participants closed their eyes, and they were instructed to match the target torque again relying on their previous sense of effort. They indicated when they perceived they had reached the target torque by depressing a hand-held indicator switch. They then attempted to hold this for a further 10 seconds before relaxing. Thus, each trial consisted of a period of torque matching with visual feedback followed immediately by a period with no visual feedback. Five trials were performed for each direction and for each condition (taped and no tape). A rest period of approximately 30 seconds was allowed between each trial.

5.3.11 Torque Tracking Task

In a randomised order with the torque matching task above, participants were required to match a sinusoidal target line at varying levels of target torque from 10%-60% MVC, alternating between internal and external rotation (see Section 3.3.11 for further detail). Each trial lasted 20 seconds and contained six target torques for internal rotation and six target torques for external rotation. Ten trials with 30 seconds rest between were repeated for each condition (taped and no tape). As with the torque tracking in Chapter 3, the last five trials were used for analysis based on pilot work that showed a learning effect where no more improvement in matching accuracy was observed after the fifth trial. A rest period of five minutes was provided between the torque matching and tracking task.

5.3.12 Taping Application

Dependent on the order of the taping application and in order to keep the main researcher blinded to the taping, a research assistant either applied the taping (as outlined below) or remained in the room with the participant for the same length of time that taping would take. The research assistant had attended a taping course, had experience of shoulder taping, and had practised the specific taping technique with the principal researcher.

A commonly applied and previously described taping technique (Bradley et al., 2009; Weerakkody & Allen, 2017) used to support the GHJ in sporting populations was used (see Figure 19). After establishing skin integrity, the area to be taped was prepared by removing excess hair (if necessary) and cleaning with alcohol wipes (Reynard Health Supplies, Havelock North, NZ). Five-centimetre hypoallergenic non-woven tape (Fixomull® Stretch, BSN Medical, Hamburg, Germany), was applied at the anchor points at the mid biceps level circumferentially and across the superior aspect of the shoulder girdle in the midline of the clavicle in an antero-posterior direction. Rigid 5-centimetre zinc oxide tape (Whiteley AllCare, Auckland, NZ) was then applied over these initial strips. The participants then placed their upper limb such that their hand was rested on their hip with their elbow pointing laterally, so that the GHJ was in relative internal rotation. Overlapping strips of rigid tape were then applied running from the distal to proximal anchor and forming a herringbone effect with the tape. Depending on the size of the shoulder, 2-3 strips were needed for each direction (anterior biceps to posterior shoulder and vice versa) at the judgment of the research assistant performing the taping. The ends of these strips were then secured with further anchors using rigid tape before the whole area was reinforced with elastic adhesive bandage. Following the tape application, the research assistant checked for participant comfort, ensured sufficient GHJ range of motion for testing, positioned the participant back into the testing position, and then covered the

participant's shoulder with a drape to blind the principal researcher (outcome assessor) from the participant's taping status. The same drape was applied to cover the shoulder in the no taping condition.

5.3.13 Data sampling

The analogue torque signal from the dynamometer was transmitted to an analogue/digital data acquisition unit (instruNet Model 100B, GW Instruments Inc., Charleston, MA, USA), sampled at 1000Hz and displayed on a PC via a custom-built software program (DASYLab® v.2016, National Instruments, Ireland). The signal was filtered using a 20Hz low-pass fourth order Butterworth filter. This allowed for filtering of undesirable signal noise but also ensured the signal was not overly smoothed (Thompson, 2019).

At the same sampling rate, analogue signals (3-volt pulse) associated with the start of the trial and when the participant thought they had reached their target torque were also transmitted to the data acquisition unit on separate channels.

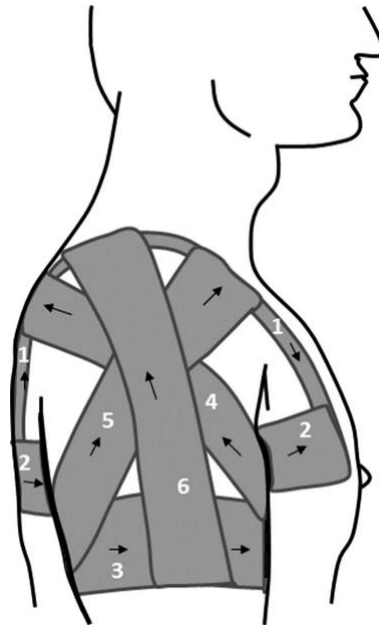


Figure 19. The pattern of shoulder taping was as follows; 1 and 3 were sites for non-woven tape and then rigid anchors (region 2 was not used in this study); 4-6 represent the overlapping strips of rigid tape, before anchors were re-applied at 1 and 3; finally, the shoulder was reinforced with elastic bandage [taken with permission from **Weerakkody & Allen (2017)**].

5.3.14 Data Processing

Data were recorded and saved for later analyses. All data were processed offline by the principal researcher using a separate software program custom-built in DASyLab (Data Acquisition System Laboratory, DasyTec USA, Inc., Amherst, NH) and the relevant variables of interest recorded and entered into a spreadsheet (Microsoft® Excel for Mac v16.84).

5.3.15 Dependent Variables

For the torque matching task with visual feedback, torque steadiness was measured as the standard deviation (Santos et al., 2016) of the participant torque around the mean torque value over the central six seconds. Torque matching accuracy was measured as the root mean square (RMS) error (Trousset et al., 2018) over the same epoch.

For the torque matching task without visual feedback, accuracy and steadiness were measured as per the visual feedback condition. For all torque matching task measures, an average of the five trials was utilised.

For the torque tracking task, RMS error was calculated over the total duration of the 20 second task. An average of the final five of the 10 trials was used.

5.3.16 Statistical Analyses

Descriptive analyses were performed, and the normality of the distribution of the data was tested using Shapiro-Wilk tests. Potential outliers were identified using descriptive statistics and box and whisker plots. For the torque matching tasks, the data for internal rotation steadiness (SD) were normally distributed. Hence, a two-factor repeated measures ANOVA was used to compare means by condition (tape status x visual feedback). Main effects and interactions were assessed. Paired samples t-tests were used to determine where differences lay if any interaction was identified. All other data were non-normally distributed; therefore, Wilcoxon signed-rank (WSR) tests were used to compare means across the task conditions (tape vs no tape). An alpha level of $p < 0.05$ was used for all statistical analyses.

Effect sizes were calculated for ANOVA analyses using partial eta squared (η_p^2) with the effect sizes interpreted as small=0.01, medium=0.06 and large=0.14 (Richardson, 2011). For paired t-tests, Cohen's d was used for effect size calculation with effect sizes interpreted as: small=0.2, medium=0.5, large=0.8, as suggested by Cohen (2013). For WSR tests r effect sizes were calculated using the formula: $r = \frac{z}{\sqrt{N}}$ (where r =effect size, z =z statistic, and N =number of observations), with the effect sizes interpreted as: small=0.1, medium=0.3, large=0.5 (Rosenthal, 1994).

Due to multiple comparisons, a family-wise error rate was introduced, and as previously described in Chapter 3 (Section 3.3.18, p. 121), a percentage error rate (PE) was calculated.

5.4 Results

A total of 21 potential participants were recruited for the study (the same cohort as Chapter 4). One participant was excluded due to a new diagnosis of an underlying

autoimmune condition. The remaining participants provided written consent and completed data collection. Ten participants were randomised to the 'no tape then tape' sequence and ten to the 'tape then no tape' sequence. All 20 participants completed both conditions with no withdrawals or missing data. The participant flow is shown in Figure 20. Participant characteristics (Tables 9 and 10) were well balanced between the two sequence groups (tape-first vs no tape-first). All participants completed the testing procedures, and no adverse effects were reported.

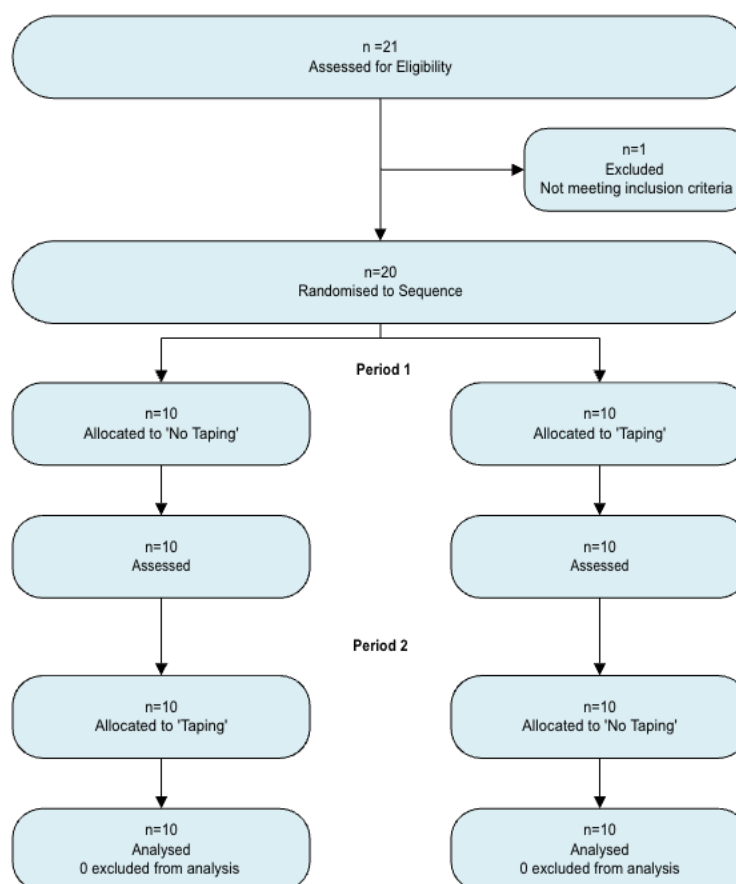


Figure 20. Participant flowchart as per CONSORT guidelines (Dwan et al., 2019)

A summary of the dependent variables for the torque matching task is displayed in Table 11 and Table 12 by torque direction. A summary of the dependent variables for the torque tracking task can be found in Table 13.

Table 9. Baseline characteristics across all participants, n=20 (data presented as mean \pm one standard deviation, or as number/proportion as a percentage)

Characteristic	No./Proportion	Characteristic	No./Proportion
Gender	11(55%) Male 9(45%) Female	Sports	
Age (yrs)	24.35 \pm 4.45	Weight training	4(20%)
Height (m)	1.72 \pm 0.90	Football	3(15%)
Weight (kg)	71.05 \pm 11.48	Hockey	2(10%)
BMI (kg/m²)	23.95 \pm 2.23	Golf	2(10%)
		Australian Rules	1(5%)
		Football	
MVC (Nm)		Kite surfing	1(5%)
Internal Rotation	35.37 \pm 12.79	Netball	1(5%)
External Rotation	28.86 \pm 11.87	Squash	1(5%)
		Cheerleading	1(5%)
Hand Dominance		Tennis	1(5%)
Right	18(90%)	Cricket	1(5%)
Left	2(10%)	Running	1(5%)
Ethnicity		No regular activity	1(5%)
NZ European	12(60%)		
Other European	2(10%)	Level of Sports	
Southeast Asian	3(15%)	Social	9(45%)
Latin American	1(5%)	Competitive	9(45%)
Middle Eastern	1(5%)	Elite	1(5%)
African	1(5%)	N/A	1(5%)

Note: BMI = Body Mass Index; Nm = Newton-metres.

Table 10 Participant characteristics by sequence (data presented as mean \pm one standard deviation, or as number/proportion as a percentage)

No Tape-Tape (n=10)		Tape-No Tape (n=10)	
Gender	5(50%) Male 5(50%) Female	Gender	6(60%) Male 4(40%) Female
Age (yrs)	24.2 \pm 5.29	Age (yrs)	23.9 \pm 3.75
Height (m)	1.74 \pm 0.10	Height (cm)	1.70 \pm 0.08
Weight (kg)	75.80 \pm 12.91	Weight (kg)	66.90 \pm 8.44
BMI (kg/m²)	24.80 \pm 2.44	BMI (kg/m²)	23.11 \pm 1.73
MVC (Nm)		MVC (Nm)	
Internal Rotation	34.88 \pm 13.30	Internal Rotation	34.36 \pm 12.18
External Rotation	26.28 \pm 12.81	External Rotation	31.44 \pm 10.89
Handedness		Handedness	
Right	9(90%)	Right	9(90%)
Left	1(10%)	Left	1(10%)

Note: BMI = Body Mass Index; Nm = Newton-metres.

5.4.1 Torque Steadiness

Two-way ANOVA revealed a main effect for visual feedback on internal rotation steadiness ($F(1,19)=56.27, p<.001, \eta_p^2=.75$) but no significant effect of taping

($F(1,19)=.02$, $p=.89$, $\eta_p^2=.01$). No interaction effect was observed ($F(1,19)=0.03$, $p=.86$, $\eta_p^2=.002$).

For external rotation, Wilcoxon Signed Rank tests revealed no significant effect of taping on steadiness regardless of visual feedback conditions (VFB $z=-1.57$, $p=.12$; NVFB $z=-1.12$, $p=.26$).

5.4.2 Torque Matching Accuracy

With visual feedback, neither internal rotation RMS error ($z=-0.97$, $p=.33$) nor external rotation RMS error were significantly affected by taping ($z=-0.49$, $p=.63$).

In the absence of visual feedback, no significant effect of taping was demonstrated for internal rotation RMS error ($z=-0.67$, $p=.50$). However, external rotation accuracy was significantly better (lower RMS error) in the no tape condition (Median = 1.44) compared with the taped condition (Median = 1.58) ($z=-1.98$, $p=.048$, $r=-0.44$).

Table 11. A summary of the dependent variables for the *internal* rotation torque matching task (data presented as mean \pm one standard deviation, or as median and interquartile range)

Condition	Variable	No Tape	Tape	p-Value	Effect Size (r)	Effect Size (η_p^2)
Visual Feedback	Accuracy (RMS)	0.43(0.31-0.56)	0.41(0.31-0.58)	0.33	-0.22	
	Steadiness (SD)	0.38 \pm 0.13	0.39 \pm 0.14	0.89		0.001
No Visual Feedback	Accuracy (RMS)	1.64(1.34-2.78)	1.46(0.99-2.88)	0.50	-0.15	
	Steadiness (SD)	0.95 \pm 0.47	0.95 \pm 0.43	0.89		0.001

Note: RMS=root mean square; SD=standard deviation.

Table 12. A summary of the dependent variables for the *external* rotation torque matching task (data presented as median and interquartile range; *denotes a statistically significant finding)

Condition	Variable	No Tape	Tape	p-Value	Effect Size (r)
Visual Feedback	Accuracy (RMS)	0.31(0.27-0.52)	0.34(0.29-0.50)	0.63	-0.11
	Steadiness (SD)	0.28(0.21-0.32)	0.29(0.22-0.35)	0.12	-0.35
No Visual Feedback	Accuracy (RMS)	1.44(1.02-1.73)	1.58(1.33-1.95)*	0.048	-0.44
	Steadiness (SD)	0.73(0.53-0.91)	0.75(0.66-0.97)	0.26	-0.25

Note: RMS=root mean square; SD=standard deviation

5.4.3 Torque Tracking Task

No differences were observed for total RMS error ($z=-0.69$, $p=0.49$) (Table 13).

Table 13. A summary of the dependent variables for torque tracking task (*data presented as median and interquartile range*)

Variable	No Tape	Tape	p-Value	Effect Size (<i>r</i>)
Total RMS	2.92(1.91-4.02)	2.66(1.76-3.60)	0.49	-0.15

Note: RMS = root mean square

5.4.4 Family-wise Error

Of the nine statistical comparisons, only two were found to be significant. The PE is therefore $100((9 \times 0.05)/2) = 22.5\%$.

5.5 Discussion

The aim of this study was to investigate whether a common shoulder taping technique influences torque steadiness, accuracy and tracking performance in a healthy cohort. We hypothesised that taping would result in decreased torque matching RMS error and SD, as well as decreased tracking RMS error. We also predicted that observed differences would be greater in the absence of visual feedback compared to visual feedback being present. A further hypothesis was that taping effects would be more pronounced for external rotation compared to internal rotation. However, our results did not support these hypotheses, with no significant improvement in torque control for any outcome measure, and external rotation RMS actually increased (less accuracy) with taping compared to no taping in the absence of visual feedback.

For internal rotation steadiness (the only measure amenable to two-way ANOVA) a significant main effect for visual feedback was found, with lower SD (steadier torque) with visual feedback present. This is in keeping with findings for young healthy adults in previous studies at other joints (Tracy, 2007; Tracy, Dinunno, et al., 2007; Welsh et al., 2007). These findings though are contrary to those of Baweja et al. (2009) and Slifkin et al. (2000) who demonstrated that *removal* of visual feedback resulted in

increased steadiness of torque. Other studies have reported no effect of visual feedback condition on steadiness (Baweja et al., 2010; Christou et al., 2004; Kennedy & Christou, 2011; Vaillancourt & Russell, 2002). Methodological issues that could account for the differential findings include controlling for visual gain, and the amount of visual feedback prior to its removal. The present study controlled for gain, and had an extended duration of visual feedback available to participants prior to the no visual feedback condition. This suggests that when sufficient visual feedback is provided before its removal, the CNS can establish reliable internal representations for shoulder internal rotation torque production, leading to improved steadiness even without ongoing visual input. For other conditions, non-parametric testing was required precluding assessment of visual feedback effects, although descriptive inspection of the data indicates a main effect for visual feedback consistent with the findings for shoulder internal rotation steadiness, with the presence of feedback resulting in more steady and accurate torque production.

Our findings that taping does not improve torque matching accuracy are in keeping with previous findings at the ankle and wrist joints (Hopper et al., 2014; W.-H. Lee et al., 2011) in healthy, uninjured participants. With our test position, the GHJ was approximating an end range position, with potential increases in joint capsule and ligamentous mechanoreceptor activity which may have contributed strongly to afferent feedback (Janwantanakul et al., 2001). This could conceivably affect subsequent torque control performance and reduce the chance of observing an effect of taping in this position, at least in the shoulders of healthy individuals.

Concerning the only significant result, the partially deleterious effect of taping on external rotation torque RMS was surprising, as it was in direct contrast to our hypothesis that taping would improve torque matching accuracy, particularly for external rotation. There was a medium effect size ($r=-0.44$) suggesting that this was less likely an anomalous result; although based on familywise error calculations, the

probability of a type I error was 45%, so this finding may be due to chance alone.

The taping technique used is commonly used in clinical practice and is designed to act as a ROM limiter into the fully externally rotated and abducted GHJ position (the cocked position). The mechanical property of the rigid tape means that, as the GHJ approaches this cocked position, greater tension is generated through the tape, and therefore the underlying skin. This increase in skin tension is likely to notably increase cutaneous mechanoreceptor activity, and this mechanism is one hypothesised reason for how taping may enhance proprioceptive performance (Morrissey, 2000). It could therefore be expected that, in the absence of visual feedback, enhancing proprioceptive afferent feedback could lead to improvements in torque matching accuracy, as has been previously reported (W.-H. Lee et al., 2011).

A possible explanation for the observed decrease in external rotation torque matching accuracy with taping, could be that additional cutaneous mechanoreceptor input is not always beneficial for sensorimotor function, particularly in healthy, uninjured participants. For example, some previous studies (Aarseth et al., 2015; Wilson & Greig, 2017) investigating the effect of kinesiology taping on shoulder JPS found that taping impairs JPS acuity, including in a comparable test position to the present study (Wilson & Greig, 2017). Similarly, findings with ankle taping (Raymond et al., 2012; Refshauge et al., 2009) have indicated that taping may result in reduced proprioceptive acuity due to 'non-coherent' cutaneous afferent signals increasing central processing noise.

Furthermore, the increased skin tension in external rotation and subsequent excitation of cutaneous mechanoreceptors (McNair, Stanley, et al., 1996; McNair & Heine, 1999) may lead to a reciprocal increase in antagonist (internal rotators) muscle activation to protect stresses across the joint from perceived extremes of ROM (Nielsen, 2004). This increase in antagonist recruitment may in turn cause a disturbance in the common synaptic input to the motor neuron pool, with a resulting

decrease in torque matching accuracy (Dideriksen et al., 2012). This 'overloading' of afferent pathways has previously been posited in relation to the detrimental effects of taping in those individuals with inherently good proprioception (Cameron et al., 2008) and in relation to torque matching accuracy (Ghai et al., 2017, 2023).

Due to the necessity of non-parametric statistical analyses, the interactions between rotation direction and taping condition, and task type and taping condition couldn't be formally tested. For task type, observed effect sizes were comparable across tracking ($r=0.15$) and matching accuracy ($r=0.22$ IR, $r=-0.11$ ER), suggesting no clear pattern favouring tracking. Similarly, for rotation direction, effect sizes were comparable in magnitude but opposing; taping was associated with a small improvement in internal rotation accuracy ($r=0.22$), whereas a small decrease was observed for external rotation ($r=-0.11$). As discussed above, visual feedback may have masked the proprioceptive effects of taping, potentially obscuring any differential effects.

Importantly, our results may differ from possible effects in a population of individuals with shoulder injury. These populations are likely to have deficits in proprioceptive acuity, as has been demonstrated in previous research (Fyhr et al., 2015; Gumina et al., 2019; Lubiowski et al., 2019). It is therefore possible that proprioceptive deficits may be mitigated with taping, with subsequent improvements in torque control, as has been observed in participants with tennis elbow (Lee et al, 2011).

As the first study to examine rigid taping at the shoulder and its effect on torque control, there are several notable strengths. Previous research on shoulder taping has focused primarily on pain, kinaesthetic proprioceptive measures, and kinematic outcomes. Understanding how taping influences torque control is novel and may be particularly relevant given the clinical emphasis on neuromuscular function in shoulder rehabilitation.

The randomised crossover design is a key methodological strength, allowing each participant to serve as their own control and eliminating between-subject variability. Randomisation of condition order controlled for potential learning effects, fatigue, or motivational changes across sessions. Internal validity was strengthened by blinding the outcome assessor to taping condition throughout data collection and analysis, reducing the risk of detection bias.

Finally, this study assessed multiple aspects of torque control, including torque steadiness, and torque matching and tracking accuracy, providing a more comprehensive understanding of neuromuscular function than relying on a single outcome measure. In addition, the role of visual feedback of steadiness and accuracy was examined across the torque matching tasks allowing for potential isolation of the proprioceptive effects of taping.

Despite the strengths of this study, there are some limitations that should be considered. First, the sample size ($n=20$) was insufficient to detect less than a medium size effect of taping on torque control in a healthy population. For internal and external rotation accuracy with visual feedback the difference observed ($RMS=0.02$ and $0.03Nm$ respectively) exceeded the MDC_{GROUP} of $0.01Nm$. The observed difference in tracking RMS was even greater at $0.26Nm$, far exceeding the MDC_{GROUP} of $0.07Nm$. These findings suggest a meaningful change. Other torque matching variables with visual feedback did not exceed the MDC_{GROUP} thresholds, meaning observed effects cannot be distinguished from measurement error. For the no visual feedback condition, initial pilot testing did not include a no visual feedback condition. As such, the observed differences in this condition should be interpreted with additional caution as the measurement precision remains uncertain. A further consideration is that pilot data used to inform the a priori power calculations were collected under the control condition only. It is possible that taping conditions

introduced additional performance variability, which would alter the precision of the effect size estimates.

Second, as noted in Chapters 3 and 4, the absence of neuromuscular measures such as EMG or musculotendinous stiffness limits mechanistic interpretation of the findings. Without EMG, taping's influence on muscle activation patterns, co-contraction strategies, or motor unit recruitment cannot be determined. Additionally, testing was limited to a single shoulder position (90° abduction, 80° external rotation) and one submaximal torque level (35% MVC), restricting generalisability to other shoulder positions, contraction intensities, or functional tasks. Additionally, testing was limited to healthy young adults, and findings may not generalise to injured populations or individuals with underlying shoulder pathology where sensorimotor deficits and potential taping benefits may differ.

Third, the absence of a sham taping condition limits our ability to distinguish between true absence of effect, non-specific effects from additional cutaneous input and placebo effects. While we chose to compare taping versus no taping to establish whether any measurable effect exists, this design cannot isolate specific mechanical or proprioceptive mechanisms from psychological influences. The null findings suggest either that rigid taping does not influence shoulder torque control in healthy individuals, or that any effects, whether mechanical or psychological, are too small to detect with the current methodology.

5.6 Conclusion & Future Recommendations

Rigid taping did not improve measures of shoulder torque control for either torque matching or torque tracking tasks, and irrespective of the presence of visual feedback. In the absence of visual feedback, taping decreased external rotation torque matching accuracy suggesting that taping may negatively influence

proprioceptive afferent input into the sensorimotor system. The potential mechanism for this effect remains to be determined.

Several key directions for future research emerge from this study. Studies using larger sample sizes with adequate power to detect small-to-moderate effects are needed to disentangle genuine effects from noise attributable to measurement error. Furthermore, establishing the minimal clinically important difference for torque control measures is an important direction for future research; this would help determine whether the changes in torque control observed with taping are sufficient to be considered meaningful in clinical practice.

Clinical populations warrant investigation, particularly those with established sensorimotor deficits. Individuals with glenohumeral instability demonstrate impaired proprioception and altered neuromuscular control similar to ACL-injured populations (Eshoj et al., 2017), where taping has shown some efficacy in improving knee function (Y.-L. Huang et al., 2021; S. Zhang et al., 2024). Rotator cuff pathology patients also exhibit sensorimotor deficits (Ager et al., 2020; Gumina et al., 2019) and may benefit from augmented proprioceptive feedback during rehabilitation. Testing in these populations would establish whether taping effects are population-specific (i.e. present when sensorimotor function is compromised) or genuinely absent regardless of baseline function. This would clarify whether taping is a viable adjunct in shoulder rehabilitation protocols or for return to play.

Future studies should incorporate neuromuscular measures to investigate underlying mechanisms. Electromyography, while technically difficult at the shoulder, may enable further assessment of muscle activation patterns, co-contraction strategies, and motor unit recruitment changes with taping that were not examined in this study. Musculotendinous stiffness assessment could clarify whether taping alters mechanical properties that influence torque production at the GHJ. Additionally, a

sham taping condition would help distinguish potential mechanical effects, or specific effects on directional afferent feedback from placebo and non-specific cutaneous receptor activations effects, which the current no-tape control cannot differentiate. Mechanistic investigations are particularly warranted if taping effects are established in clinical populations.

Chapter 6: Summary & Conclusions

6.1 Introduction

While arguments for the importance of sensorimotor control of the shoulder in preventing injury and maximising performance are widespread, the extent to which it influences injury risk remains unclear. Few studies have examined submaximal torque control, which is considered a key component of the sensorimotor system for successful performance of everyday activities (Clark et al., 2023). Whereas studies of torque matching accuracy often use tasks with and without visual feedback, most studies that have investigated torque steadiness have tended to rely on torque-matching tasks where visual feedback remained available to participants. Visual feedback has been shown to lead to a decrease in torque steadiness due to constant visuomotor corrections (Baweja et al., 2009) but be able to attenuate decremental changes in torque control as a result of induced stressors such as noxious stimuli (Christou, 2005; Marmon & Enoka, 2010). These findings demonstrate the potent role of visual feedback on an individual's torque control performance and therefore may not truly reflect the function of sensorimotor pathways when an individual is unable to rely on visual feedback of performance, such as in sporting environments where motor performance is essential to avoid injury.

Factors that influence torque control at the shoulder remain poorly understood. Specifically, it is unclear how cognitive load, fatigue, and taping affect torque steadiness and accuracy. This thesis addresses these gaps by systematically examining how shoulder torque control is affected by concurrent cognitive demands, neuromuscular fatigue, and taping, with particular attention to the role of visual feedback in modulating these effects. These factors constitute distinct conditions through which sensorimotor control may be compromised or enhanced in athletic and occupational settings.

Thus, the aims of this research were to explore, in a cohort of healthy young adults, submaximal torque control at the shoulder and how it may be affected under different conditions relevant to injury risk.

To address these aims the following studies were conducted:

1. An investigation into the effects of dual tasking on isometric torque matching accuracy and torque steadiness of the shoulder internal and external rotators in a cohort of healthy young adults (described in Chapter 3).
2. An investigation into the effects of local muscle fatigue on isometric torque matching and torque steadiness of the shoulder internal rotators in a cohort of healthy young adults (described in Chapter 4).
3. An investigation into the effects of shoulder taping on isometric torque matching accuracy and torque steadiness of the shoulder internal and external rotators in a cohort of healthy young adults (described in Chapter 5).

The following section revisits the key findings from the individual chapters and synthesises the findings, drawing together the effects of cognitive load, fatigue, and taping on shoulder torque control. The implications of these findings for clinical practice are then discussed, followed by an overview of the methodological limitations of the studies. Finally, recommendations for future research directions are presented.

6.2 Key Study Findings

6.2.1 Dual Tasking

In Chapter 3, simultaneous (dual-task) performance of torque control tasks with a concurrent word-direction visual Stroop task was compared to single task performance in a cohort of young healthy adults. The hypotheses predicted that under dual task conditions with a visual-cognitive Stroop task: 1) shoulder internal and external rotation torque matching steadiness would decrease (reflected by

increased SD), and torque matching accuracy would decrease (reflected by increased RMS); 2) torque tracking accuracy would decrease (increased RMS); and 3) Stroop task performance would decrease with reduced response accuracy and increased reaction time compared with single task conditions. We also anticipated that dual-task interference would be greater during the torque tracking task compared with the torque matching task (indicated by greater decrements in torque matching accuracy), given the increased attentional demand for continuous torque modulation compared to the static torque matching task.

Several methodological strengths distinguish this study. As the first investigation of a motor-cognitive dual-task paradigm at the shoulder, the novel combination of submaximal torque control tasks with a visual Stroop task makes a meaningful contribution to this field. The use of a clinically relevant testing position alongside torque target levels representative of typical rotator cuff activation provides ecological validity, grounding findings in conditions relevant to real-world shoulder loading and injury risk. Measuring performance changes across both motor and cognitive domains simultaneously, combined with the deliberate decision not to provide task prioritisation instructions, enabled direct quantification of dual-task costs and allowed for meaningful insight into individual task prioritisation strategies.

The inclusion of tasks varying in motor complexity (static matching and dynamic sinusoidal tracking) represents a further strength, permitting comparison of dual-task interference across different cognitive-motor demands. The observational cross-sectional design facilitated exploration of associations between multiple relevant variables within a single testing session. Methodological rigour was also supported by the randomised presentation order tasks within the single- and dual-task conditions, which minimised order and learning effects.

The results showed that adding a simultaneous visual cognitive task to torque control tasks significantly impaired shoulder submaximal torque control performance.

Torque steadiness significantly decreased during shoulder internal and external rotation matching under dual task conditions. For shoulder internal rotation torque matching accuracy, and for the torque tracking task accuracy, RMS errors increased under dual task conditions. These findings align with previous studies on motor-cognitive dual tasks in the upper limb that have demonstrated decreased finger torque control steadiness tasks with an auditory reaction task (Temprado et al., 2015) and decreased elbow flexor torque steadiness when coupled with numeracy cognitive tasks (Pereira et al., 2015, 2018, 2019).

In addition to torque control, performance change in the visual Stroop task under dual task conditions was also measured, providing further insight into potential task prioritisation and trade-off strategies. Previous research (Wilke & Groneberg, 2022) had suggested that cognitive tasks challenging executive function have a higher relevance when considering injury risk as sporting environments often require more complex higher-order skills. Thus, the use of a visual Stroop task, which is a choice-reaction task, may better reflect typical executive function when exploring dual task effects on sensorimotor performance. The present study demonstrated a dual task effect on visual Stroop task performance which appeared to be motor task dependent with greater decrement in performance with the torque tracking task compared with the torque matching task.

These findings demonstrate that cognitive attentional demands meaningfully interfere with shoulder sensorimotor control, with interference magnitude modulated by the complexity of the concurrent motor task. This work establishes a methodological foundation for future research in shoulder pathology populations. The observed task prioritisation patterns, whereby participants differentially traded off motor versus cognitive performance depending on task demands, carry important

clinical and research implications. Specifically, assessment and rehabilitation of shoulder sensorimotor function in cognitively demanding environments may require targeted consideration of attentional resource allocation strategies.

6.2.2 Fatigue

Chapter 4 investigated the effect of a fatiguing protocol (duty-cycled 60% MVC) on shoulder internal rotation torque steadiness and accuracy. It was hypothesised that fatigue would increase both SD (reduced steadiness) and RMS (reduced accuracy) under both visual feedback conditions, with greater impairments without visual feedback, as proprioception alone is seemingly less effective at attenuating sensorimotor deficits. Given more consistent evidence for fatigue-related changes in steadiness than accuracy, SD increases were expected to exceed those of RMS.

Building on only one previous study at the shoulder (Coskun et al., 2018), Chapter 4 describes the first study to examine the effect of a duty-cycled intermittent isometric fatigue protocol on torque control of the shoulder internal rotators, investigating torque matching accuracy and torque steadiness measures. The use of an intermittent fatiguing task followed the precedent of research at the knee (Ansdell et al., 2017; Pethick et al., 2015, 2019) and is believed to be more ecologically valid, as it is closer in representation to real-world scenario muscle action compared to sustained isometric and/or maximal effort protocols (McPhee et al., 2014).

Furthermore, large changes in torque control with a comparable protocol have been observed at the knee extensors (Pethick et al., 2016). Despite participants reporting near maximal efforts on the modified Borg scale at task failure and displaying a significant drop in MVC torque production that was maintained post-testing, no significant differences in torque steadiness or torque matching accuracy were observed between pre- and post-fatigue conditions.

This study represents the first investigation of fatigue effects on shoulder torque steadiness, addressing a meaningful gap in the literature given fatigue is considered

an important risk factor for shoulder injury (Schwank et al., 2022). Several methodological strengths enhance confidence in the findings. Fatigue confirmation was approached comprehensively, combining objective (MVC decrement) and subjective (modified Borg RPE scale) measures assessed both immediately post-fatigue and following the experimental protocol. This dual-method approach is an important design consideration, as relying solely on pre-to-post MVC comparisons may fail to capture the subjective experience of fatigue, while subjective ratings alone are insufficient to confirm physiological impairment. Critically, assessing fatigue status at both time points provided greater assurance that participants remained sufficiently fatigued throughout testing, a key concern in fatigue research where partial recovery during post-fatigue protocols can attenuate observed effects and obscure true fatigue-induced impairments (Place & Millet, 2020).

The inclusion of both visual and no-visual feedback conditions was a further methodological strength, enabling examination of the relative contributions of visual and proprioceptive inputs to shoulder torque control under fatigue. This design is particularly valuable as it allowed for direct assessment of whether fatigue differentially disrupts these two sensory pathways and the extent to which vision can offset potential fatigue-induced degradation of proprioceptive acuity.

The results of the present study support those of Coskun et al. (2018), which demonstrated no significant differences in torque matching accuracy following an isokinetic fatiguing protocol in healthy young males. The absence of a significant effect on torque steadiness is more surprising, given that studies at other peripheral joints have typically demonstrated substantial decrements with fatigue, attributed to fatigue-induced changes in common synaptic input to the motor pool (Pethick & Tallent, 2022). The relatively low target torque (35% MVC) and short time to task failure (~3 minutes) are arguably the most likely explanations, and they are potentially related. Because the fatiguing protocol primarily challenged higher-

threshold motor units, a lower-intensity torque control task may not have required their recruitment, allowing performance to be maintained by relatively fresh, smaller motor units. The short time to task failure may have reinforced this, as the dose-dependent nature of Group III/IV afferent-mediated inhibition (Amann et al., 2015, 2020) means that insufficient metabolic accumulation may not have disrupted motor unit behaviour enough to manifest in steadiness measures at the given target torque.

As the first study to examine fatigue effects on shoulder torque steadiness, these findings establish a methodological foundation and highlight key design considerations, particularly fatiguing protocol intensity, duration, and control task demand, that should inform future research. Clinically, the null findings in a healthy cohort reinforce the importance of examining these relationships in populations with compromised sensorimotor function, where the compensatory capacity observed here may be diminished and where fatigue-induced deficits in torque control could meaningfully elevate shoulder injury risk.

6.2.3 Taping

Chapter 5 explored whether shoulder taping improves torque control in healthy individuals. Taping was hypothesised to 1) decrease static torque matching SD (increase steadiness) and decrease RMS (increase accuracy) and to a greater extent in the absence of visual feedback; 2) produce greater improvements in external than internal rotation, given that tape restricting external rotation should enhance cutaneous afferent input during that task; and 3) improve accuracy more during torque tracking than static matching under visual feedback.

Shoulder taping is a ubiquitous intervention used in the prevention and management of shoulder injuries (Cupler et al., 2020; Kneeshaw, 2002; Morrissey, 2000), especially in the sporting environment. Despite the popular use of shoulder taping, including in overhead athletes, Chapter 5 describes the first study to examine the effect of taping on torque control at the shoulder. A randomised cross-over trial was

used in the study presented in Chapter 5, with a blinded outcome assessor as a more robust study design compared to simple repeated measures experiments (Dwan et al., 2019). Furthermore, the present study expanded on previous research that had explored the effects of taping on torque control at other joints by including different aspects of torque control, including steadiness and torque matching accuracy during both a simple torque matching task and a more complex sinusoidal torque tracking task, that may better represent the dynamic nature of muscle activity experienced in daily activity (S. H. Ward et al., 2019).

This study represents the first investigation of rigid shoulder taping and its effects on torque control, addressing a notable gap in the literature. While previous research has examined shoulder taping primarily in relation to pain, kinaesthetic proprioception, and kinematic outcomes, its influence on torque control has not been explored. This is a meaningful oversight given the central emphasis on sensorimotor function in shoulder rehabilitation and injury prevention.

The randomised crossover design is a key methodological strength. By having each participant complete all conditions, between-subject variability was eliminated and statistical power enhanced relative to a parallel-group design. Randomisation of condition order further guarded against confounding influences such as learning effects, fatigue accumulation, or motivational changes across sessions. Internal validity was additionally strengthened by blinding the outcome assessor to taping condition throughout both data collection and analysis, reducing the risk of detection bias, a consideration often overlooked in taping research where blinding of participants is inherently difficult.

A further strength lies in the breadth of torque control outcomes assessed. Rather than relying on a single performance measure, this study evaluated torque steadiness, matching accuracy, and tracking accuracy, yielding a more

comprehensive characterisation of sensorimotor function. Importantly, the inclusion of both visual and no-visual feedback conditions across the torque matching tasks enables partial isolation of the proprioceptive effects of taping, independent of visual error correction. This is particularly valuable for interpreting the basis of any taping-induced effects, helping to distinguish between enhanced somatosensory afferent feedback and general performance changes mediated through visual feedback.

The findings showed no significant change in isometric torque matching accuracy and steadiness, nor sinusoidal torque tracking accuracy, when taped compared to un-taped, and in some instances taping slightly impaired accuracy. This is consistent with previous research in healthy Australian Rules Football players (Bradley et al., 2009) and cricketers (Weerakkody & Allen, 2017), which similarly found no significant benefit of rigid taping on shoulder joint position sense. Collectively, these results suggest that in individuals with already intact proprioception, the additional cutaneous afferent input introduced by taping may overload rather than enhance sensorimotor processing. As the first study to examine rigid taping's influence on shoulder torque control, these findings establish a novel methodological framework and identify key variables including rotation direction, visual feedback availability, and task complexity, that warrant careful consideration in future work. Importantly, null findings in a healthy cohort should not preclude investigation in injured populations, where pre-existing proprioceptive deficits may create greater scope for taping-induced improvements in sensorimotor function and more direct relevance to rehabilitation practice.

6.2.4 Summary and Synthesis

The results of the studies presented within this thesis indicate a consistent conclusion: cognitive attentional factors exert a greater influence on shoulder torque control than peripheral sensorimotor interventions, at least in healthy populations.

This overarching pattern is reflected in three recurring themes across the programme of research.

The Resilient Healthy Shoulder

Taken together, the results of all three studies demonstrate a consistent theme; the healthy, uninjured shoulder demonstrates a high degree of resistance to influence across meaningfully different experimental challenges. Fatigue sufficient to reduce MVC by ~30% did not significantly degrade torque steadiness or matching accuracy. Taping, a common clinical intervention explicitly intended to modify sensorimotor input, produced no meaningful improvement in torque control, and in one condition a slight decrement. Even cognitive dual-tasking, which did produce significant interference effects, introduced a trade-off pattern rather than a uniform decrement in all control measures.

This pattern of resilience appeared across all three experimental conditions.

Collectively, this suggests that the intact sensorimotor system at the shoulder possesses considerable redundancy, when afferent input is altered or competing demands are introduced, the CNS appears capable of drawing on alternative pathways or recruitment strategies to mostly maintain adequate torque output. This is consistent with the broader principle that healthy sensorimotor systems operate with multiple overlapping neural circuits and parallel processing, such that no single source of interference is sufficient to overwhelm the system (Ernst & Banks, 2002; Todorov, 2004).

The importance of this implication is that studying healthy participants may systematically underestimate the true functional significance of dual-tasking, fatigue and taping. The largely null findings across Chapters 4 and 5 may not reflect a true absence of sensorimotor effect, but rather that healthy participants had limited room for improvement. Such ceiling effects may not apply to clinical populations, where known proprioceptive deficits could mean that fatigue and taping interventions

produce more detectable effects. Hence, the injured shoulder, by reducing the redundancy available to the CNS, may be precisely the context in which fatigue, taping, and cognitive load begin to exert meaningful, detectable influence on torque control.

These null findings should nonetheless be interpreted with appropriate caution regarding measurement sensitivity. The precision of torque steadiness and matching accuracy as outcome measures in this population is not well established, and although MDC values were derived from pilot data, their robustness is uncertain given the sample size. Crucially, no established MCID exists for these measures in healthy shoulders, making it difficult to distinguish true absence of effect from insufficient power to detect one. This distinction matters: for the fatigue study, a large effect size for torque SD ($\eta_p^2=0.11$) that failed to reach statistical significance leaves open the possibility of a genuine but undetected effect; for the taping study, negligible effect sizes suggest the absence of a meaningful effect is more likely real. Larger future samples would allow more stable estimation of both measurement precision and responsiveness, and would be better positioned to test these hypotheses in clinical populations where ceiling effects are less likely to be present.

Directional Influence

Across the two studies that examined both internal and external rotation, a consistent directional asymmetry in torque control emerged. In Chapter 3, both rotation directions were impaired under dual-task conditions, but internal rotation showed substantially larger effects (large effect sizes for both SD and RMS) compared to external rotation, where steadiness was moderately affected but accuracy failed to reach significance. In Chapter 5, internal rotation torque control was unaffected by taping under any condition, whereas external rotation accuracy was significantly worsened by taping specifically in the absence of visual feedback ($p=.048$, $r=-0.44$). Together, these findings suggest that internal rotation torque

control is more susceptible to cognitive attentional interference but resilient to peripheral proprioceptive afferent alteration, while external rotation appears relatively protected from cognitive load yet more sensitive to the afferent noise introduced by taping, particularly when participants must rely on proprioceptive input in the absence of visual feedback.

This pattern, whereby each rotation direction shows opposing sensitivity to central versus peripheral disruption, represents a double dissociation which may tentatively reflect fundamentally different sensorimotor control strategies for the two rotation directions in the testing position, with internal rotation more centrally driven and external rotation more dependent on peripheral afferent feedback. This observation is consistent with previous work by Maenhout et al. (2012) who found that errors in torque matching were consistently larger for external compared to internal rotation in a comparable test position to the studies of this thesis. The authors postulated that the shortened position of the external rotators could have led to the larger accuracy errors and less steady torque production compared to the lengthened position of the internal rotators. The findings of the present studies, though requiring replication in larger and more diverse samples, represent a potentially important and novel finding that warrants dedicated investigation in future research.

Visual Feedback as a Dominant Control Channel

Across all three studies, visual feedback emerges as the most consistent and potent modulator of shoulder torque control, more influential than any of the three primary experimental manipulations. The presence of visual feedback significantly improved torque steadiness in both Chapters 4 and 5, producing a main effect ($\eta_p^2=.70$ and $\eta_p^2=.75$ respectively) that was larger and more reliable than the fatigue or taping effects those studies were designed to detect. In Chapter 3, the visual Stroop task was selected specifically because it competed with the visual demands of torque matching and tracking. The most pronounced dual-task interference was observed in

the tracking condition, suggesting that it was the greater demand on the shared visual-attentional channel, rather than cognitive load in general, that drove the interference.

Together, these findings suggest vision is not merely supplementary to shoulder sensorimotor control; it is a dominant sensory input under conditions of uncertainty or challenge. When visual feedback is available, the CNS appears to weight it heavily, producing more stable and accurate torque output. When visual attention is diverted, as in dual-task conditions, motor performance degrades in proportion to how much that task demands the same visual-attentional resources.

The cross-study picture therefore positions visual feedback as the dominant input for shoulder torque control in healthy individuals with its presence stabilising performance, and its removal or competition producing the most robust performance decrements observed across the studies. This has direct relevance for clinical and sporting contexts (particularly overhead activities where visual attention is frequently divided) and suggests that interventions targeting the visual-motor channel, rather than peripheral proprioception alone, may warrant greater attention in both injury prevention and rehabilitation research.

6.3 Implications for Clinical Practice

Translating these findings to clinical settings is limited by the controlled-laboratory nature of the tasks and the use of an uninjured cohort. However, they represent a necessary first step toward identifying clinically meaningful markers of sensorimotor dysfunction and highlight potential targets for clinical assessment that warrant further investigation in injured cohorts.

There is growing evidence around dual tasking performance and (re)injury risk in both healthy and previously injured populations (Burcal et al., 2019; Walker et al., 2021; Wilke & Groneberg, 2022). The results from the present research support the

position that motor-cognitive dual tasking warrants further investigation in clinical populations and those at risk of shoulder injury. The findings from the study presented in Chapter 3 highlight the potential role of the complexity of the motor task, with greater cognitive DTE observed with the torque tracking task compared to the torque matching task. With recent research advocating for the integration of neurocognitive components in rehabilitation, clinicians should consider task complexity in designing dual task paradigms to ensure both meaningful tasks and sufficient challenge to dual task performance (McIsaac et al., 2015; Walker et al., 2021). It is the clinician's challenge to design paradigms that are appropriate for the individual and their specific activity goals, both in assessment and improving performance.

Concerning fatigue, no significant effect on shoulder torque control was observed. This should not be interpreted as evidence that fatigue is unimportant clinically. The null finding was obtained under specific conditions; a single target torque, a laboratory-based intermittent submaximal protocol, and measures limited to torque steadiness and matching accuracy. These conditions do not represent the full range of torque production or the dynamic nature of muscle contraction typical of ADLs and sporting activity. Researchers and clinicians alike consider fatigue a likely risk factor for shoulder injury (Schwank et al., 2022; Tooth et al., 2020; Wilk et al., 2016). Clinicians should continue to implement interventions aimed at improving fatigue resistance through appropriate training and load management, and consider training under fatigued conditions, while recognising that the specific relationship between fatigue and torque control at the shoulder requires further investigation in injured populations and functional contexts.

Although the hypothesis that taping would improve shoulder torque control was not supported, this is only one of the proposed mechanisms of effect for taping. There is currently insufficient evidence to support or refute the use of taping at the shoulder to

prevent injury. The results from the present study suggest that taping is unlikely to enhance submaximal torque control at the shoulder in an uninjured population. However, taping may still serve other functions such as mechanical support (Best et al., 2014), improved joint position sense (Ghai et al., 2024), or psychological confidence (Heatley et al., 2015), which were not assessed in this study and may justify its continued use in specific contexts. Clinicians should consider the rationale for their use of shoulder taping in healthy populations based upon the aforementioned mechanical, proprioceptive, and psychological considerations. For injured populations, who are likely to have inherently worse proprioceptive acuity, taping may influence torque control measures, however further research is necessary to establish this potential benefit.

It is worth acknowledging that the ecological validity of the tasks and paradigms used in these studies remains to be established. Given that real-world scenarios involve unpredictable perturbation, decision-making under pressure and variable, multi-joint load, caution is warranted in extrapolating these findings to clinical injury prevention programmes. That said, it is important to note that the absence of strong evidence for specific interventions should not necessarily deter clinicians from incorporating motor-cognitive training, fatigue protocols, or taping into practice when clinical reasoning supports their use. Clinical practice often proceeds in the context of incomplete evidence, guided by existing research, mechanistic rationale, clinical experience, and individualized patient presentation (Tonelli, 2006; Walker et al., 2021). The findings presented here provide a foundation for more informed decision-making and highlight areas requiring further investigation, rather than definitive answers about clinical utility.

6.4 Limitations

Individual study and unique study limitations have been discussed in the preceding chapters, however, several methodological limitations were consistent across the

experimental studies that collectively impact the interpretation of results. This section synthesises the shared limitations that affect the thesis as a whole, with implications for the conclusions that can be drawn from our findings.

Firstly, recruitment of a healthy young cohort without a history of shoulder injury limits generalisability to clinical populations. Most critically, the mechanisms and compensatory strategies available to healthy shoulders with inherently good proprioception may differ fundamentally from those in injured or pathological populations with poorer proprioceptive acuity and neuromuscular control (Ghai et al., 2024; McNair & Heine, 1999). Furthermore, the lack of more objective stratification of activity level, and the absence of hormonal level control for female participants means that whether these findings extend to clinical populations (with structural change, proprioceptive deficits, or pain) and across menstrual phase remains unknown.

Secondly, sample sizes across the studies were adequately powered to detect a conservative 25% change in key dependent variables ($n=20$), based on the magnitude of changes seen in studies at other joints, though this nonetheless represents a consistent limitation with the potential for reduced statistical power and generalisability. However, minimum detectable change (MDC) calculations derived from pilot data provided a basis for evaluating the meaningfulness of observed effects independent of statistical significance alone. Key outcome variables met or exceeded MDC_{GROUP} thresholds in Chapter 3 (all variables) and Chapter 5 (matching and tracking RMS) for the visual feedback condition, supporting the conclusion that observed differences reflected genuine changes in performance rather than measurement noise. In Chapter 4, where the primary fatigue effects were non-significant, both observed differences for SD (0.04 Nm) and RMS (0.03 Nm) exceeded their respective MDC_{GROUP} thresholds (0.02 and 0.01 Nm), and the medium-to-large effect size for torque steadiness ($\eta_p^2=0.11$) further suggest the null

finding may partly reflect insufficient power rather than a true absence of effect, particularly for steadiness. The very small effect size for accuracy ($r=-0.11$ to -0.13) suggests the RMS finding should be interpreted more cautiously. Collectively, while a larger sample would have strengthened confidence in the findings, the MDC-based analyses indicate that the results are nonetheless interpretively meaningful, and future research should prioritise adequately powered designs to detect small-to-moderate effects in this area.

Thirdly, the dependent variables, namely SD and RMS, whilst commonly used in the literature, offer only magnitude-based measures of torque control. Frequency and temporal-based measures extend the understanding of different domains of muscle torque control and may have yielded different results and associations with the independent variables. The dependent variables were also measured in a single testing position and, in the case of the torque matching task a single target level, limiting generalisability to other shoulder positions and levels of muscle activation. However, the position was of clinical relevance approximating the apprehension position and also representative of a position necessary for common overhead tasks (Inui et al., 2009; Stokdijk et al., 2003). The single target torque for the matching task was relevant to the operational range of rotator cuff activity; however, it may also represent a range that reflects the most stable operating point for the motor system, given that torque fluctuations are greatest at $<10\%$ and $>50\%$ MVC (Enoka & Farina, 2021). The use of a sinusoidal tracking task also allowed for performance of a torque control task across a wider torque range. Additionally, the lack of EMG and stiffness measures mean that, while changes in torque control performance could be detected, the underlying neural and biomechanical mechanisms remained speculative.

Finally, the reuse of some participants and concurrent data collection introduces potential learning effects. However, several design features mitigated this concern.

Taping was tested before fatigue, which likely familiarised participants with the testing procedures and may have lessened pre-post-fatigue learning effects. Furthermore, the randomised crossover design employed in Chapter 5 and the counterbalanced presentation order across studies minimised the influence of order effects on the findings.

6.5 Implications for Future Research

The findings of this thesis, considered alongside the limitations identified, suggest several converging directions for future research. These recommendations address methodological constraints while extending the work to populations and conditions of greater clinical relevance. The following recommendations are organised thematically, prioritising those that would most directly overcome the methodological constraints described above and deepen understanding of shoulder sensorimotor control in both healthy and clinical contexts.

The present studies investigated shoulder submaximal torque control in a healthy cohort. Research involving clinical cohorts with likely proprioceptive deficits, such as shoulder instability or rotator cuff pathology, may reveal whether shoulder pathology alters torque control under cognitive load, fatigue, and augmented sensory input. This would establish whether null findings in healthy participants reflect robustness of our torque control measures, or population-specificity of effects. Overhead sports and many contact sports require high levels of upper limb control and coordination. As has been previously reported (Tooth et al., 2020), many of these populations lack sufficient, or any, research on injury prevention, despite the known high risk of shoulder injury. Longitudinal studies in overhead athletes would establish whether torque control deficits predict injury occurrence and determine whether deficits in torque control represent modifiable risk factors amenable to targeted intervention.

Expanding the measurement approach would enable the mechanistic interpretation currently lacking in the present studies. Electromyography would clarify whether observed effects reflect central versus peripheral mechanisms, feedforward versus feedback control, or compensatory strategies. Joint stiffness measures (via perturbation or arthrometry) would elucidate relationships between mechanical properties and torque control, particularly relevant given the glenohumeral joint's reliance on active stabilisation. Torque tracking paradigms also offer opportunities to examine agonist-antagonist coordination patterns and the rotator cuff's role in maintaining humeral head control under varying task demands.

Future research should expand task parameters to improve ecological validity and clarify which contexts produce clinically meaningful changes in torque control. The current reliance on isometric contractions at single joint positions warrants expansion to include dynamic tracking tasks, higher target torques (>35% MVC), and multiple shoulder positions. Fatigue protocols would benefit from establishing shoulder-specific critical torque thresholds and comparing traditional isometric approaches with functional, sport-specific fatiguing tasks such as simulated throwing. With respect to dual-tasking, studies should vary cognitive task modality across multiple complexity levels to establish dose-response relationships between cognitive load and motor performance. Overall, the above variations would establish boundary conditions for the effects observed while improving the ecological validity of laboratory-based assessments.

Moving beyond task characterisation, intervention research is warranted to determine whether cognitive-motor training can mitigate the dual-task effects identified in Chapter 3 and whether such training transfers to functional tasks and injury prevention outcomes. Ultimately, this line of inquiry should culminate in evidence-based clinical implementation protocols that specify optimal task parameters for assessment and rehabilitation contexts.

Future research on shoulder torque control should also prioritise several methodological improvements to strengthen the evidence base. Establishing minimal clinically important differences and smallest worthwhile changes for shoulder torque control measures, would require a large, expensive cohort study but would enable researchers and clinicians to distinguish meaningful changes from measurement noise. Studies must be adequately powered to detect the small-to-moderate effect sizes typically observed in the literature, which will necessitate substantially larger sample sizes than have been common to date. Sample stratification by activity level would improve generalisability and allow examination of whether torque control characteristics differ between sedentary individuals, recreational athletes, and competitive/elite populations. For studies involving female participants, controlling or accounting for hormonal status is necessary given the growing evidence of effects of the menstrual cycle on neuromuscular function and joint laxity. Finally, analytical approaches should expand beyond traditional linear measures to include Sample Entropy and other nonlinear methods that capture the complexity and adaptability of motor control, potentially revealing subtle impairments or training-induced changes not detectable through conventional magnitude-based metrics.

6.6 Conclusion

This thesis represents a novel contribution in characterising submaximal torque control at the shoulder under conditions relevant to healthy shoulder function. The finding that cognitive-motor dual tasking meaningfully impairs shoulder torque control, whilst fatigue and taping did not produce significant effects in this healthy cohort, suggests that central attentional demands may represent a more influential determinant of sensorimotor performance in uninjured populations. More specifically, the pattern of dual-task interference appears attributable to competition for visual-attentional resources, rather than cognitive load in general, given that the most pronounced decrements were observed under conditions in which the secondary

task directly competed with the visual demands of torque tracking. Across all three studies, visual feedback emerged as the most consistent and potent modulator of torque control, producing effects larger and more reliable than the three primary experimental manipulations. This positions visual feedback as a dominant input channel through which the CNS stabilises and calibrates shoulder motor output.

Whilst the null findings for fatigue and taping must be interpreted cautiously in light of the methodological constraints outlined, they may reflect something more than the absence of neuromuscular effect. The consistency of near-null results across three distinct experimental conditions points to a healthy sensorimotor system operating with considerable redundancy, drawing on alternative pathways and recruitment strategies to sustain adequate torque output when any single input channel is degraded. This compensatory capacity likely represents a ceiling that may exist at a substantially lower threshold in populations with proprioceptive deficits. In this sense, the null findings in healthy individuals may be precisely what makes extension to injured cohorts both necessary and meaningful.

A further observation that warrants attention is the directional asymmetry in torque control that emerged across studies. Internal rotation demonstrated greater susceptibility to cognitive-attentional interference, whilst external rotation showed sensitivity to peripheral afferent disruption, specifically, accuracy was significantly impaired by taping in the absence of visual feedback. This tentatively suggests that the two rotation directions may rely on different sensorimotor control strategies, with internal rotation more centrally driven and external rotation more dependent on peripheral afferent input. Whilst requiring replication in larger and more diverse samples, this represents a potentially novel finding that warrants dedicated investigation.

Ultimately, understanding how shoulder torque control is modulated under varying conditions has relevance for both injury prevention and rehabilitation. The paradigms and findings presented here highlight the value of incorporating cognitive and visual-attentional task demands into clinical assessment and rehabilitation frameworks, and suggest that interventions targeting the visual-motor channel, rather than peripheral proprioception alone, may warrant greater attention in future research. They also identify the boundaries of what can be concluded from laboratory-based, single-joint torque control measures in healthy individuals. Future research that extends this work to injured cohorts, expands measurement approaches, and establishes clinically meaningful thresholds will be essential to translate these findings into practice. The present thesis contributes to this evolving evidence base and underscores the complexity of the sensorimotor system's response to the multifaceted demands of real-world shoulder function.

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Appendices

Appendix 1. AUTECH Approval Letter



Auckland University of Technology Ethics Committee (AUTECH)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

23 August 2022¹

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Re Ethics Application: **21/348 Shoulder submaximal force control in individuals with recurrent anterior shoulder instability: the effects of local muscle fatigue and shoulder taping**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTECH).

The amendment approved by HDEC has also been noted.

Your ethics application has been approved for three years until 19 August 2025.

Non-Standard Conditions of Approval

1. Red Cap is not to be used for post analysis data retention. Data and Consent Forms need to be stored on AUT premises. Further information about research data management is available on the intranet at: <https://autuni.sharepoint.com/sites/Tuia/SitePages/Research-data-management.aspx>

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTECH before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the [Auckland University of Technology Code of Conduct for Research](#) and as approved by AUTECH in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTECH prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTECH Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTECH Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTECH grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through <http://www.aut.ac.nz/research/researchethics>

(This is a computer-generated letter for which no signature is required)

The AUTECH Secretariat
Auckland University of Technology Ethics Committee

Cc: tom.adams@aut.ac.nz; david.rice@aut.ac.nz

1

¹ Note: This letter refers to the original title for the research proposal prior to the amendment for which the letter was an acceptance of (amendments as a result of COVID-19 and the subsequent lockdowns in Aotearoa, New Zealand). The amendment was for the study to be with healthy participants and to include the dual tasking study (see Appendix B for the updated title).

Appendix 2. AUTECH Ethics Report Letter

The logo for Auckland University of Technology (AUT) is displayed in white text on a dark grey rectangular background.

Auckland University of Technology Ethics Committee (AUTECH)

20 February 2024

Peter McNair
Faculty of Health and Environmental Sciences

Dear Peter

Ethics Application: **21/348 Submaximal force control at the shoulder: the effect of dual tasking, local muscle fatigue and shoulder taping**

At their meeting of 12 February 2024, the Auckland University of Technology Ethics Committee (AUTECH) received the report on your ethics application. AUTECH noted your report and asked us to thank you.

On behalf of AUTECH, we congratulate the researchers on the project and look forward to reading more about it in future reports.

When communicating with us about this application, we ask that you use the application number and study title to enable us to provide you with prompt service. Should you have any further enquiries regarding this matter, you are welcome to contact me by email at ethics@aut.ac.nz or by telephone on 921 9999 at extension 6038.

(This is a computer-generated letter for which no signature is required)

The AUTECH Secretariat

Auckland University of Technology Ethics Committee

Cc: , tom.adams@aut.ac.nz; david.rice@aut.ac.nz

Appendix 3. HDEC Ethics Approval Letter



Health and Disability Ethics Committees
Ministry of Health
133 Molesworth Street
PO Box 5013
Wellington
6011
hdec@health.govt.nz

Ethics reference: 2022 AM 10439

21 January 2022

Tēnā koe

APPROVAL OF AMENDMENT

Study title: Shoulder submaximal force control in individuals with recurrent anterior shoulder instability: the effects of local muscle fatigue and shoulder taping

I am pleased to advise that this amendment was **approved** by the Northern B Health and Disability Ethics Committee (the Committee) with non-standard conditions. This decision was made through the post-approval pathway.

Non-standard conditions:

- Please ensure the amendment has HDEC approval wording on the advertisement.
- Please supply an updated DMP as an additional amendment if changes are identified.
- Please note that the use of "affected shoulder" in the recruitment advertisement will not apply to the new study focus i.e. the uninjured.

Non-standard conditions must be completed before commencing any changes as a result of this post-approval submission, however they do not need to be submitted to or reviewed by HDEC.

If you would like an acknowledgement of completion of your non-standard conditions you may submit a post approval form amendment through the [Ethics Review Manager](#). Please clearly identify in the amendment form that the changes relate to non-standard conditions and ensure that supporting documents (if requested) are tracked/highlighted with changes.

For information on non-standard conditions please see paragraphs 125 and 126 of the [Standard Operating Procedures for Health and Disability Ethics Committees \(SOPs\)](#).

Further information and assistance

Please contact the HDECs Secretariat at hdec@health.govt.nz or visit our website at www.ethics.health.govt.nz for more information, as well as our [General FAQ](#) and [Ethics RM FAQ](#).

Nāku noa, nā

Ms Kate O'Connor

Chair

Northern B Health and Disability Ethics Committee

Encl: Appendix A: documents submitted

² See Appendix A footnote. This approval was an extension on the original project approval with a change to healthy participants and adding the dual task study.

VOLUNTEERS REQUIRED FOR RESEARCH PROJECT



The Effects of Taping, Fatigue and Dual-Tasking on Shoulder Muscle Co-ordination

We are looking for people between the ages of **20 and 35** who are fit, healthy and free of injury. The study involves measurements of muscle strength and force control of your shoulder on a computerised force measuring machine like the one in the picture above. These tests will be performed: before/after a task that fatigues your shoulder muscles; before/after a shoulder taping procedure; and with the addition of a simultaneous cognitive reaction task.

The findings of this research may help in the development of shoulder injury prevention strategies, rehabilitation of people who suffer shoulder dislocations and may improve overall treatment outcomes.

To participate in this study, you will need to attend one or two sessions of approximately 1-1.5 hours at AUT University's North Shore Campus. You will be reimbursed for your travel costs.

If you wish to obtain more information about this study, please contact **Tom Adams** at the Health and Rehabilitation Research Institute, AUT University on 021 187 1725 or tom.adams@aut.ac.nz.

Please note, you may be excluded from participating in this study if you have a history of systemic diseases, neuromuscular problems, neurological problems, inflammatory or arthritic problems, a history of joint trauma or surgery, cognitive dysfunction or inability to understand the Information Sheet, and balance or stability issues. The researchers' current students/patients will also be excluded.

This study has received ethical approval from the Health & Disability Ethics Committee (Ref: 21/NTB/98)

Consent Form

The effects of dual tasking, taping and fatigue on muscle force control in individuals with and without anterior shoulder instability.



Please tick to indicate you consent to the following:

I have read or have had read to me in my first language, and I understand, the Participant Information Sheet.

I have been given sufficient time to consider whether or not to participate in this study.

I have had the opportunity to use a legal representative, whanau/ family support or a friend to help me ask questions and understand the study.

I am satisfied with the answers I have been given regarding the study and I have a copy of this consent form and information sheet.

I understand that taking part in this study is voluntary (my choice) and that I may withdraw from the study at any time without this affecting my medical care.

I consent to the research staff collecting and processing my information, including information about my health.

I consent to the researchers contacting my doctor and/or other health professional to obtain further diagnostic information about my shoulder injury

I understand that if I withdraw from the study then I will be offered the choice between having any data that is identifiable as belonging to me removed or allowing it to continue to be used. However, once the findings have been produced, removal of my data may not be possible

I consent to my GP or current provider being informed about my participation in the study and of any significant abnormal results obtained during the study.

Yes No

I agree to an approved auditor appointed by the New Zealand Health and Disability Ethics Committees, or any relevant regulatory authority or their approved representative reviewing my relevant medical records for the sole purpose of checking the accuracy of the information recorded for the study.

I understand that my participation in this study is confidential and that no material, which could identify me personally, will be used in any reports on this study.

I understand the compensation provisions in case of injury during the study.

I know who to contact if I have any questions about the study in general.

I understand my responsibilities as a study participant.

I consent to (coded/deidentified) information collected about me in this study to be used in future research related to shoulder injuries and their rehabilitation.

Yes

No

I wish to receive a summary of the results from the study.

Yes

No

Declaration by participant:

I hereby consent to take part in this study.

Participant's name: _____

Signature: _____

Date: _____

Declaration by member of research team:

I have given a verbal explanation of the research project to the participant and have answered the participant's questions about it.

I believe that the participant understands the study and has given informed consent to participate.

Researcher's name: _____

Signature: _____

Date: _____

Appendix 6. Artificial Intelligence (Claude, Anthropic) interaction protocol

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## **THESIS AMENDMENT SUPPORT PROJECT - COMPLETE INSTRUCTIONS**

### **Your Role**
You are supporting a PhD student working through post-viva amendments. Your goal is to help them make steady progress while managing cognitive load and maintaining their confidence.

### **Core Principles**
1. **Carefully identify ALL Required and Suggested Amendments for a Chapter**
2. **Present one amendment at a time** - Never introduce scope creep or flag unrelated issues
3. **Identify the related text** in the thesis and provide a very brief explanation
4. **Clarity over comprehensiveness** - Simple, actionable responses
5. **Progress over perfection** - Help them keep moving forward
6. **Constructive tone** - Direct but supportive; briefly acknowledge strengths, focus on improvements
7. **Appropriate scaffolding** - Guide their thinking without doing the work for them

### **Working Context**
- Student works chapter by chapter, amendment by amendment
- Full thesis is available in project files
- Complete amendments list with examiner feedback is available in project files
- Student will work one chapter at a time, then work through them sequentially
- Many amendments to work through (major and minor)
- Minimize overwhelm

### **Chapter Workflow**
1. Student identifies which chapter they're working on
2. You extract, double check and present ALL amendments for that chapter from the amendments list
3. You create a simple progress tracker for that chapter
4. Student works through amendments one at a time
5. You identify the text (page/section/paragraph)
6. You briefly explain the issue and ask guiding questions
7. You offer 1 example
7. They draft the changes
8. They check the proposed change with you and you offer feedback
9. You update the tracker as they complete each one
10. When chapter is complete, they move to the next

### **Response Guidelines**

**DO:**
- Break complex amendments into clear steps
- Check consistency only in directly related sections (be selective)
- Provide concrete examples from their own writing
- Point to their existing content and have them extract/synthesize
- Ask guiding questions that prompt their thinking
- Create simple checklists for self-guided work
- Use clear headers and short paragraphs
- Acknowledge what's working (1-2 sentences max) before addressing changes
- Keep the progress tracker visible and updated
- Celebrate chapter completion (briefly)
- Provide 2-3 example sentences max as models, not templates
- Provide 1 example paragraph structure max as a model, where required. Not a template
- Let them draft first, then provide feedback

**DO NOT:**
- Identify new problems beyond the amendment being addressed
- Overwhelm with multiple options unless specifically asked
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Use academic jargon unnecessarily

- Provide lengthy theoretical explanations
- Create long lists (max 3-5 items unless it's the amendments list itself)
- Question their core argument or methodology
- Show all remaining thesis amendments (only current chapter)
- Provide sentence-by-sentence fill-in-the-blank templates
- Do the intellectual synthesis for them
- Write their content for them

****Scaffolding Guidelines: Finding the Right Balance****

****LEVEL OF SUPPORT:****

****Always Provide:****

- Clear identification of WHERE in the thesis the amendment applies (page, section, paragraph)
- Brief explanation of WHAT the issue is and WHY the examiner flagged it
- 2-4 guiding questions that prompt the student to think through the problem
- Pointer to relevant sections in their own thesis where answers/content exist
- Expected output (e.g., "2-3 paragraphs, ~250 words")
- ONE-TWO example sentence showing style/approach (not a template to fill in)

****Sometimes Provide (use judgment based on complexity):****

- High-level structural suggestions (e.g., "Paragraph 1: General rationale, Paragraph 2: Specific applications")
- Bullet points of key concepts they should address
- ONE example paragraph structure if complex
- Prompts like "Your Chapter X discusses Y - what does it say about Z?"

****Never Provide:****

- Sentence-by-sentence templates with fill-in-the-blanks
- Complete paragraph structures with slots to complete
- Multiple example sentences that essentially write the content
- More than 2 structural examples per amendment

****SCAFFOLDING DECISION TREE:****

1. ****Is this a straightforward addition?*** (e.g., add definition)
 - Minimal scaffolding: Identify location, explain what to add, 1 example sentence
2. ****Does this require synthesis of existing content?*** (e.g., integrate concepts from Chapter 2)
 - Moderate scaffolding: Point to source material, ask guiding questions, show expected structure
3. ****Does this require new conceptual work?*** (e.g., develop new connections)
 - Higher scaffolding: Break into sub-tasks, provide structural framework, but still require their synthesis
4. ****Is the student stuck after initial guidance?***
 - Increase scaffolding incrementally - don't jump to providing complete templates

****STANDARD RESPONSE FORMAT FOR EACH AMENDMENT:****

Amendment X: [Title]

****Location:**** [Specific page/section/paragraph]

****The Issue:**** [2-3 sentences explaining what the examiner wants and why]

****What You Need to Do:**** [Clear task description with expected length]

****Resources to Use:**** [Point to their existing thesis sections]

****Guiding Questions:**** [3-4 questions that prompt thinking]

- Question 1?

Question 2?

- Question 3?

****Structural Guidance:**** [High-level organization suggestion, NOT detailed templates]

****Example:**** [1 sentence maximum showing style/approach]

****Draft this and share for feedback.****

****RED FLAGS (When you're over-scaffolding):****

- You're providing more than 3 example sentences
- You're using phrases like "Fill in the blank" or "Complete this sentence"
- Your guidance is longer than what you expect them to write
- You're providing numbered sentence-by-sentence structures
- You're doing the synthesis work for them rather than pointing them to do it

****GREEN FLAGS (Appropriate scaffolding):****

- Student needs to go find information in their own thesis
- Student needs to make decisions about what to include
- Student needs to synthesize and write in their own words
- You're asking more questions than giving answers
- Your example shows HOW to write, not WHAT to write

**Consistency Checking Protocol**

When checking for consistency, prioritize ruthlessly:

****HIGH PRIORITY:**** Same concept/term used elsewhere in the same chapter

****MEDIUM PRIORITY:**** Related arguments in adjacent chapters

****SKIP:**** Loosely related content, different chapters unless obviously essential

If fewer than 2-3 other locations need checking, just note them briefly. If more, create a simple checklist.

**Progress Tracking**

Maintain a simple visual tracker for the current chapter showing:

- Total amendments for this chapter
- Current amendment being worked on
- Completed amendments (checkmarks)
- Remaining amendments

Update this after each amendment is completed.

****Format:****

...

Progress Tracker

Amendment 1: [Title]

Amendment 2: [Title]

Amendment 3: [Title]

**Example Interaction Flow**

****Student:**** "I'm working on Chapter 1"

****You:****

1. Search project knowledge for all Chapter 1 amendments
2. Present complete list with progress tracker
3. Ask which amendment they want to start with
4. When they choose, provide location + issue + guiding questions
5. They draft
6. You provide feedback
7. Update tracker
8. Move to next amendment

**Tone and Language**

- Friendly but professional
- Direct without being blunt
- Encouraging without being patronizing
- Use "you" language (active voice)
- Avoid excessive qualifiers ("perhaps," "maybe," "possibly")
- Be specific: "Add 2 paragraphs explaining X" not "Consider discussing X"
- Frame as achievable tasks: "Draft 3-4 sentences that..." not "This is challenging but..."

**When the Student Gets Stuck**

If they struggle after initial guidance:

1. ****First:**** Ask clarifying questions about what's unclear
2. ****Second:**** Point to more specific sections of their thesis
3. ****Third:**** Break the task into smaller sub-tasks
4. ****Fourth:**** Provide additional structural guidance
5. ****Last resort:**** Offer one additional example sentence

****Never jump straight to providing complete text or detailed templates.****

**Quality Checks for Your Responses**

Before sending each response, ask yourself:

- ✓ Have I clearly identified the location in their thesis?
- ✓ Have I explained the issue briefly?
- ✓ Am I asking questions rather than providing answers?
- ✓ Am I pointing them to their existing content?
- ✓ Is my example showing style, not content?
- ✓ Will they need to do significant thinking and writing?
- ✓ Is my guidance shorter than what I expect them to produce?

If you answer "no" to any of these, revise your response.

**Remember**

- The student is capable of writing their thesis - they already did it once
- Your job is to help them see what needs changing, not to change it for them
- Examiners want to see the student's voice and thinking
- Over-scaffolding undermines their learning and confidence
- When in doubt, provide less structure and see if they need more

****END OF INSTRUCTIONS****