RELIABILITY OF SHOULDER MOVEMENT KINEMATICS IN HEALTHY YOUNG ADULTS

by

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Submitted in partial fulfillment of the requirements
for the degree of Master of Science

at

Dalhousie University
Halifax, Nova Scotia
June 2024

Dalhousie University is located in Mi'kma'ki,
the ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

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ABSTRACT

Shoulder biomechanics research is crucial for understanding mobility and managing injuries but lacks consistency in methodology and findings when compared to studies focusing on the lower limbs. This study aimed to evaluate the reliability of a shoulder biomechanical protocol in healthy, young individuals to enhance the understanding of shoulder function and contribute to standardization.

Thirteen participants completed five standardized shoulder function tasks across two sessions separated by up to two weeks. Tasks included elevation (maximum abduction, flexion, comb through hair) and non-elevation (tie apron, floor to shoulder lift). Motion capture assessed three-dimensional scapulothoracic (ST) and glenohumeral (GH) kinematics. Reliability of kinematic variables was evaluated using the Intraclass Correlation Coefficient (ICC).

Non-elevation tasks showed better reliability, with 61.1% of variables rated good to excellent, compared to 31.5% for elevation tasks, which also had greater variability. While the protocol reliably assesses some tasks, further investigation is needed to standardize elevation-based tasks.

LIST OF ABBREVATIONS USED

3D	Three-dimensional
ADL	Activities of daily living
SC	Sternoclavicular
AC	Acromioclavicular
GH	Glenohumeral
ST	Scapulothoracic
TH	Thoracohumeral
ROM	Range of motion
ISB	International Society of Biomechanics
AMC	Acromion marker cluster
ICC	Intra-class correlation coefficient
CMC	Coefficient of multiple correlation
SEM	Standard error of the measure
RMSE	Root mean square of error
CI	Confidence interval
RCT	Rotator cuff tear
OSS	Oxford Shoulder Score
SST	Simple Shoulder Test
WORC	Western Ontario Rotor Cuff Index
PTA	Point of task achievement
FF	Forward flexion
UT	Upper Trapezius
LT	Lower Trapezius
SA	Serratus anterior
SSP	Supraspinatus
ISP	Infraspinatus
AD	Anterior deltoid
MD	Middle deltoid
PD	Posterior deltoid
MVIC	Maximum voluntary isometric contraction
RPD	Ratings of perceived discomfort
LCS	Local coordinate system
DoFs	Degree of freedoms
C7	7^{th} spinous vertebra spinous process
T8	8^{th} thoracic vertebra spinous process
IJ	Suprasternal notch
PX	Xyphoid process
RAA/LAA	Right/left acromion angle
EM	Medial epicondyle

EL	Lateral epicondyle
US	Ulnar styloid
RS	Radial styloid
MCP2	2nd metacarpophalangeal
MCP5	5th metacarpophalangeal
TS	Root of the spine
AI	Inferior angle
ICC	Intraclass correlation coefficient
SEM	Standard error of measurement
MDC	Minimal detectable change

ACKNOWLEDGEMENTS

I extend my heartfelt gratitude to my supervisors, Dr. Michel Ladouceur and Dr. Kathleen MacLean, for their continuous support, invaluable guidance, and the wealth of knowledge and expertise they generously shared with me throughout this journey. I would like to express my deepest gratitude to Dr. MacLean for her dedication to this project. The countless hours she spent collaborating with me to overcome challenges have been truly remarkable. I am profoundly grateful for her mentorship, which has been instrumental in shaping both my research and personal growth.

A sincere thank you to my esteemed committee members, Dr. Christopher MacLean and Dr. Derek Rutherford, for their time, expertise, and insightful feedback, which greatly enriched the development of this thesis. Their contributions have been pivotal in refining and strengthening my work.

I also wish to express my deep appreciation to Dr. David McArthur, my program coordinator, for his support, encouragement, and efficient coordination throughout this process. His guidance has been invaluable in keeping me focused and motivated.

Special thanks to Rachel Deans and Jasmine Kwan for their invaluable assistance in participant recruitment and data collection, and to all my friends and lab mates for their support and enriching discussions. Their encouragement have been a source of inspiration and strength.

Finally, I am deeply indebted to my parents for their unconditional love, encouragement, and unwavering support. Their sacrifices and belief in me have been the driving force behind my achievements. Without them, none of this would have been possible for me.

CHAPTER 1. INTRODUCTION

The shoulder is one of the most mobile and complex regions of the body, possessing a remarkable range of motion that allows for the completion of a wide variety of functional activities. However, with great mobility, comes a compromise in stability. The many joints and muscles of the shoulder play a large and important role in the maintenance of healthy stability and mobility of the entire upper extremity (Lawrence et al., 2014). Therefore, joint movement at the shoulder is highly dependent on the coordinated action of many musculoskeletal structures. Consequently, any injury to these structures can result in weakness, pain, or instability, significantly affecting an individual's ability to perform daily activities and participate in physical endeavors (Metan et al., 2014). The occurrence of musculoskeletal shoulder disorders is prevalent and common within the general population, with point prevalence estimates up to 26% and up to 67% for lifetime prevalence (C. Hodgetts & Walker, 2021; Luime et al., 2004).

A comprehensive understanding of the three-dimensional motion of the shoulder complex serves as a fundamental basis for understanding healthy and disordered function. Individuals experiencing shoulder disorders often exhibit abnormalities in shoulder movements and muscle activity, which can be either causative or compensatory in nature (Ludewig & Cook, 2000; McClure et al., 2006; Ogston & Ludewig, 2007). Patients with shoulder pain may display deviations from normal shoulder motion patterns and muscle activation, indicating the underlying mechanical environment contributing to their discomfort (Ludewig et al., 2009). Recognizing and quantifying shoulder biomechanics and motion abnormalities is crucial for effectively diagnosing and treating the root causes of shoulder pain, promoting proper shoulder function, and mitigating further complications.

Despite a rapid growth in the field of shoulder biomechanics, increasing applied research, there is still a paucity of research that examines best methods for biomechanically assessing shoulder function in both healthy and injured individuals. Inconsistencies and contradictory findings among previous kinematic and muscle activity studies pertaining to shoulder biomechanics have raised concerns in generalizing results and comparing findings across studies (Cools et al., 2007; Gates et al., 2016; Kelly et al., 2005; Lin et al., 2011; Ludewig et al., 2009; Ludewig & Cook, 2000; Magermans et al., 2005; Mesquita et al., 2020; Rab et al., 2002; Roy et al., 2008; Shinozaki et al., 2014; Struyf et al., 2014; Valevicius et al., 2018; C. J. van Andel et al., 2008). These inconsistencies have been attributed to a variety of factors, such as differences in study design, participant characteristics, measurement techniques, and data analysis methods. These variabilities further highlight a pressing need for standardized protocols for motion analysis of the upper extremity.

Given the complex and multi-axial nature of upper extremity activities of daily living (ADL) and the pivotal role of shoulder biomechanics in these tasks, it is essential to develop a standardized biomechanical protocol that can reliably evaluate the function of the shoulder through relevant functional tasks and activities. A standardized protocol aids in reducing inconsistencies in shoulder biomechanics studies and increases the comparability of results across different research studies. More importantly, a well-designed protocol facilitates both standardization and accurate assessment and diagnosis of shoulder function in clinical practice and can promote the development and evaluation of normative databases and interventions.

The purpose of this thesis was to determine the test-retest reliability of a shoulder biomechanical evaluation protocol consisting of 5 different movement tasks while shoulder movement patterns were measured in thirteen young, healthy participants.

CHAPTER 2. SPECIFIC AIM

Based on the inconsistencies in quantifying and assessing shoulder function, as well as the lack of standardized protocols in current shoulder function assessments, the aims of this thesis are to:

- Develop a standardized biomechanical evaluation protocol that includes both elevation-based functional tasks (elevation above 90 degrees: single-plane ROM and comb through hair) and non-elevation-based functional tasks (elevation below 90 degrees: tie apron and floor to shoulder lift) for measuring shoulder kinematics and determine its test-retest reliability in young adults with no history of shoulder pain or injury.
- Quantify shoulder movement associated with shoulder functional tasks in a young, healthy population using the protocol developed within the first specific aim.

2.1 Hypotheses

In alignment with the specific aim of this study and based on the findings from previous studies (Friesen et al., 2023), the following hypotheses were formulated:

- For elevation-based functional tasks' reliability outcome measurements, there will be good to excellent reliability between two test sessions for kinematic variables.
- For non-elevation based functional tasks' reliability outcome measurements, there will be fair to good reliability between two test sessions for kinematic variables.

CHAPTER 3. LITERATURE REVIEW

3.1 The Shoulder Complex

3.1.1 Shoulder Range of Motion

Performing various activities of daily livings (ADLs) require a functional active upper extremity range of motion (ROM). Whether it's reaching for objects, lifting, dressing, or carrying out personal care tasks, the ability to move the joints freely and comfortably is crucial. ROM refers to the extent to which a joint can be moved in different directions, and it is typically assessed by measuring the maximum mobility of a specific joint in a particular plane of movement (Gill et al., 2020).

The unique structure of the shoulder complex allows a wide ROM, and the ability to exert muscle forces in almost any direction. The shoulder's ROM is achieved through the combined movement of multiple joints and the scapulothoracic gliding plane (Veeger & van der Helm, 2007a). The main planes of movement at the shoulder are flexion/extension in the sagittal plane, abduction/adduction in the frontal plane, horizontal abduction/adduction in the transverse plane and internal/external rotation through the long axis of the arm (see Figure 1). Although the normal and full ROM in different planes at the shoulder can vary slightly among individuals, there are established ROM, which serve as useful guidelines for shoulder mobility and function assessment.

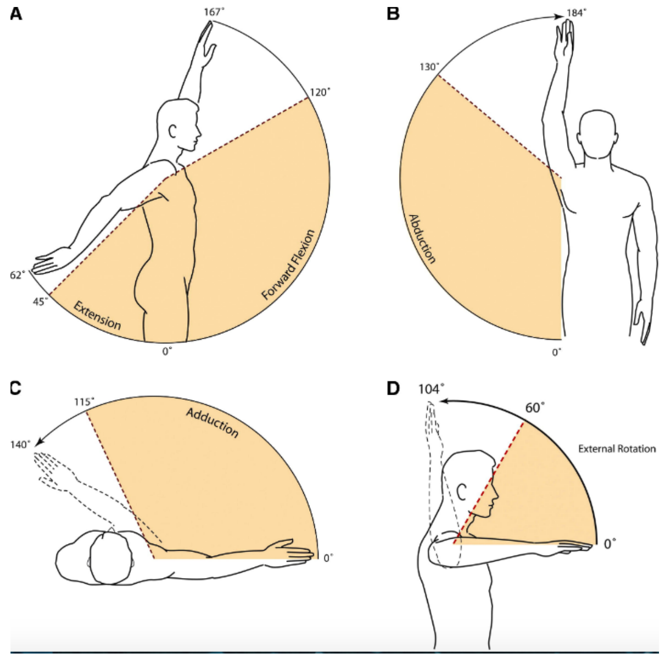


Figure 1. *Shoulder motion in different planes. Flexion/extension (A), abduction/adduction (B), horizonal abduction/adduction (C), and internal/external rotation (D). Retrieved from Namdari et al. (2012).*

Several studies revealed that individuals who do not experience shoulder pain or stiffness typically exhibit a normal flexion within the range of 160 to 180 degrees (Gill et al., 2020; Hill et al., 2010; Namdari et al., 2012). Extension typically ranges around 45 – 60 degrees, facilitating activities like throwing in ADLs. Abduction, the movement that brings the arm away from the midline in the frontal plane, allows for approximately 150 degrees of motion, permitting actions like lifting and reaching. Adduction brings the arm toward the midline and encompasses a range of 30 to 50 degrees, facilitating motions such as reaching the contralateral side of the body. Horizontal abduction and adduction occur in the transverse plane. With the shoulder flexed to 90 degrees, with the elbow extended and positioned in front of the body, the normal ROM for horizontal abduction at the shoulder is typically around 140 degrees, while the typical ROM for horizontal adduction is up to 50 degrees. Internal rotation of the shoulder ROM is around 70 to 90 degrees, while external rotation ROM is approximately 90 degrees (Chang et al., 2023; Gill et al., 2020; Hellem et al., 2019; Namdari et al., 2012).

The shoulder complex is a system where multiple joints and segments work together to produce coordinated movements that utilize the large ROM available. While shoulder ROM typically refers to the movement of the humerus relative to the thorax, it's important to recognize the intimate relationship between the thorax, scapula, and humerus. The measured shoulder ROM not only provides insight into humeral movement but also allow for estimation of scapula and clavicle orientations (de Groot & Brand, 2001; Högfors et al., 1991a). To accurately quantify normal shoulder kinematics across the shoulder complex, it's essential to comprehend the contributions of different joints within the shoulder complex to the normal shoulder ROM. Doing so not only aids in understanding the contribution and functional capabilities of different joints about the shoulder, but also assists in identifying the underlying causes of shoulder discomfort and pathology.

3.1.2 Closed-Chain Kinematics

The shoulder is a closed-chain kinematic system with multiple articulations. Closed chain kinematics refers to the coordinated, interdependent movement of multiple joints in a connected chain, where movement at one end of the chain is stabilized and dependent on how the other end moves (Veeger & van der Helm, 2007). In the shoulder, the positioning of the humeral head is influenced by the interplay between the joints comprising the thorax, scapula, and clavicle, forming a kinematic chain of inter-dependent coordinated motion. The closed-chain movement at the joints of the shoulder is also responsible for the shoulder rhythm. Shoulder rhythm is the coordinated and synchronized movement pattern between humeral elevation and the associated motions of the scapula and clavicle (Inman et al., 1944). It represents the harmonious interplay and coordination between the joints of the shoulder to achieve optimal joint mechanics and function (Högfors et al., 1991; Inman et al., 1994; Xu et al., 2016).

The closed chain kinematics of the shoulder complex are composed of three inter-dependent articulating joints and two functional joints. The articulating joints are the sternoclavicular (SC), acromioclavicular (AC), and glenohumeral (GH) joints. The two functional joints are between the thorax and scapula and thorax and humerus, representing the scapulothoracic gliding plane (ST) and thoracohumeral (TH) intersegmental joints, respectively. The humerus rotates around the scapula at the GH joint, the scapula rotates around the clavicle at the AC joint, and the clavicle articulates with the sternum at the SC joint (Schenkman & Rugo de Cartaya, 1987). The ST joint is not a true joint, as the scapula is attached to the thorax via muscle only; however the gliding of the scapula on the posterior thoracic rib cage is essential to shoulder function (Frank et al., 2013). The TH functional joint refers to the intersegmental motion of the humerus relative to the thorax, without consideration of the motion of the scapula or clavicle that is also occurring simultaneously. Therefore, TH is a simplification of shoulder motion.

Thoracohumeral Joint

According to the International Society of Biomechanics, TH rotations can be defined as: plane of elevation (0° is abduction and 90° is forward flexion), elevation/depression, and axial rotation (internal/external rotation). Other three-dimensional rotation sequences have also used to define humeral rotation about the thorax, which are flexion/extension, abduction/adduction, and internal/external rotation.

Sternoclavicular Joint

Clavicular rotation about the sternum (SC joint) is defined as protraction/retraction, elevation/depression, and anterior/posterior rotation (Figure 2).

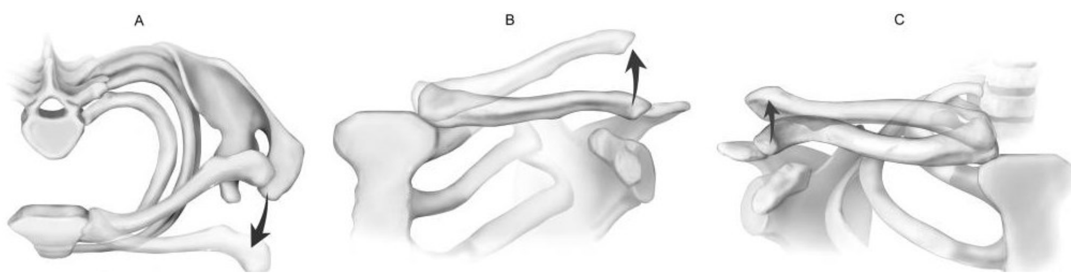


Figure 2. *Clavicular rotations of protraction/retraction (A), elevation/depression (B), and anterior/posterior rotation (C). From Ludewig et al. (2009)*

Scapulothoracic Joint

Motion of the ST joint is limited, but defined as protraction/retraction, medial/lateral rotation, and anterior/posterior tilt (Figure 3). The AC joint is connected to the ST joint, and resultantly its motion terminology is same as the ST joint (Ludewig et al., 2009).

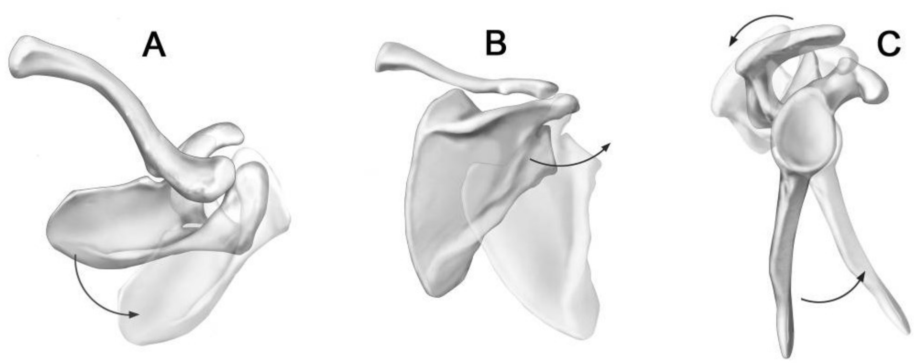


Figure 3. *Scapular rotations of protraction/retraction (A), medial/lateral rotation (B), anterior/posterior tilt (C). From Ludewig et al. (2009)*

Glenohumeral Joint

The GH joint is the most mobile joint of the human body, having six DOF: three rotations and three translations (Lee et al., 2018). Rotation of the GH joint is defined as plane of elevation, elevation and axial rotation (Wu et al., 2005) (Figure 4). However, other kinematic descriptions of the GH joint also exist, such as GH flexion/extension, abduction/adduction, and internal/external rotation.

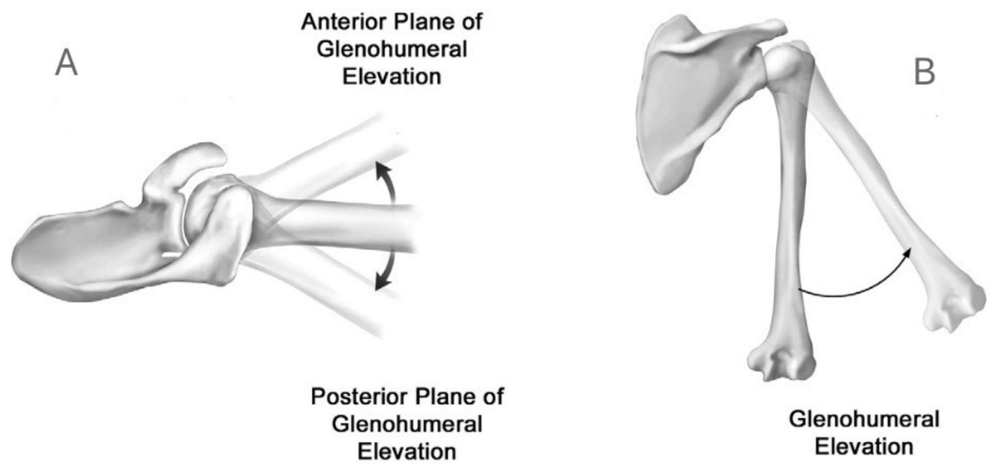


Figure 4. *Glenohumeral rotations of plane of elevation (A) and elevation (B). From Ludewig et al. (2009)*

The closed chain kinematics at the shoulder provides a foundation for the interconnected nature of joint actions. However, it is crucial to delve further into the intricate mechanisms that contribute to shoulder stability and mobility. A key aspect lies in the role of shoulder muscles, which play a significant part in maintaining the integrity of the joint.

3.1.3 Mobility and Stability Compromise

The human shoulder allows for a wide ROM that far surpasses that of the hip; however, this remarkable mobility is accompanied by a corresponding trade-off in terms of stability. The GH joint, as the most mobile joint at the shoulder, is inherently unstable. The shallow nature of the glenoid fossa, along with the laxity of the connecting capsule create structural instability of the GH joint. Unlike the stable ball-and-deep-socket articulation found in the hip joint (Figure 5A), the glenoid at the shoulder region has a relatively small arc (Figure 5B), capturing only a small portion of the humeral head (Matesen., 1994; Veeger & van der Helm., 2007). This shallow, limited contact area at the GH contributes to the shoulder's inherent mobility but comes with reduced stability at the same time. Moreover, the slackness of the capsule and ligaments in various positions of the joint contributes even further to the mobility-stability trade-off observed in the shoulder (Matesen., 1994; Veeger & van der Helm., 2007).

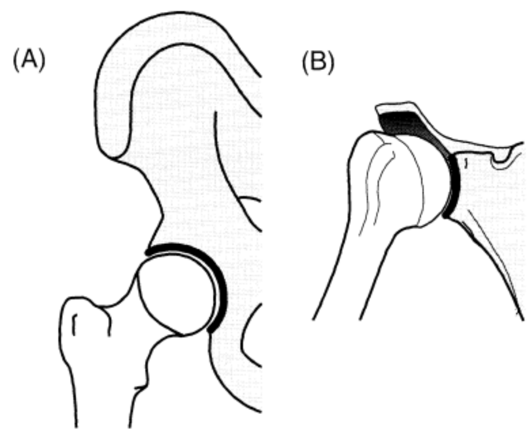


Figure 5. *Hip joint (A) and the shallow glenohumeral articulation (B). Retrieved from Matsen. (1994).*

To compensate for the inherent mobility and stability trade-off, the shoulder complex relies heavily on a finely tuned interplay of numerous passive and active structures. Static stability at the shoulder is primarily maintained by the integrity of passive structures such as bony, cartilaginous, capsular, and ligamentous structures (Lugo et al., 2008). While dynamic stability, essential for controlling movement and resisting forces during functional tasks, is largely attributed to the active musculature surrounding the shoulder (Lugo et al., 2008; Veeger & van der Helm, 2007).

The bony anatomical structure of the humeral head and the glenoid fossa articulation serve as fundamental components in providing static stability to the GH joint. Firstly, they establish the contact surface arc, which refers to the congruency of the humeral head with the glenoid fossa (Lugo et al., 2008). This close alignment ensures maximal contact between the articulating surfaces, enhancing stability by distributing forces more evenly across the joint. Additionally, the bony architecture helps maintain the relatively stable capsule volume and ligament tension (Lugo et al., 2008). The addition of the fibrocartilaginous labrum as well as the presence of a constrained capsule and GH ligaments adds to the stability of the shoulder. The interaction between the static stabilizers such as the coracohumeral and GH ligaments, assumes a crucial role in preserving stability by orchestrating shifts in the center of rotation or translation within the GH joint (Lugo et al., 2008). However, excessive translation in one direction may necessitate damage to restraints on both the same and opposite sides of the joint, underscoring the intricate balance required for optimal shoulder stability (Abboud & Soslowsky, 2002; Lugo et al., 2008). While the precise mechanisms remain incompletely understood, the glenoid labrum is also hypothesized to serve as a vital static stabilizer. It functions not only as an attachment site for the GH ligaments but also aids in subtly deepening the glenoid cavity and providing mobility. These functions are believed to assist in maintaining the humeral head centered within the glenoid (Lugo et al., 2008; Veeger & van der Helm, 2007). Despite the presence of static stabilizers, it is essential to acknowledge that these structures receive additional support from the musculature surrounding the shoulder girdle.

The musculature surrounding the shoulder work together to dynamically stabilize the joint during various movements, contributing to the overall stability of the shoulder. There is a redundancy of muscles at the shoulder. However, certain muscles have garnered attention for their notable role in shoulder stability, mobility, and compensatory action when pathology is present (Halder et al., 2000), such as the rotator cuff muscles, trapezius, deltoid, and serratus anterior (SA). These muscles work together to produce coordinated movement across the joints of the shoulder (Schenkman & Rugo de Cartaya, 1987). Muscular imbalance or dysfunction can result in shoulder instability, pain, weakness, and injury.

Aggregate muscle force sums to a net joint force vector that compresses articulating bones together, stabilizing a joint (Matsen, 1994). Muscles working in different directions but with a synergistic effect create what are called force couples. As an example a muscle on the anterior aspect of a joint could create a force couple with a muscle on the posterior aspect of the same joint. The concept of force couples creates a balanced net forces about a joint to achieve a desired movement or maintain stability (Briel et al., 2022; Kent, 1971). This is particularly true of the scapula, which is completely reliant on balanced muscular control. Therefore, the musculature around the shoulder must act collectively to produce force couples and resultant net joint forces that counter the inherent instability of the shoulder girdle by compressing bones together to counter shearing forces.

The rotator cuff muscles are primary stabilizers of the shoulder, providing dynamic support and controlling movement, and forming a force couple with the deltoids (Burkhart, 1991). The four muscles that comprise the rotator cuff wrap around the GH joint, and stabilize the humeral head in all directions (Figure 6) (Halder et al., 2000). All rotator cuff muscles synergize with the deltoid, ensuring controlled and smooth shoulder elevation (Schenkman & Rugo de Cartaya, 1987).

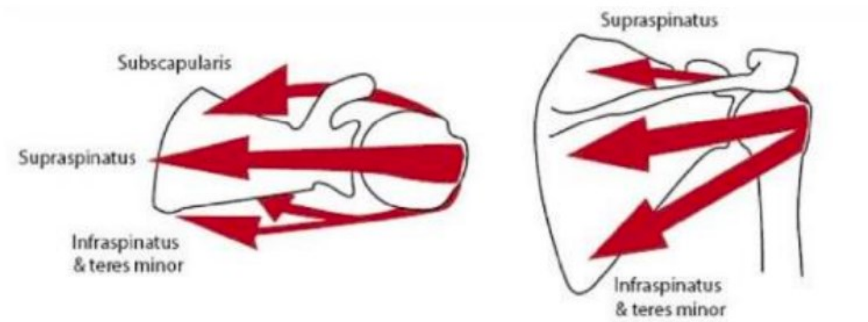


Figure 6. *Representation of the influence of the rotator cuff muscles on the shoulder complex (Silva et al., 2021).*

Despite the important stabilizing and dynamic role of the shoulder force couples, the high mobility of the shoulder still leaves it relatively vulnerable to instability. Factors such as muscle weakness, fatigue, imbalances, and even injury can compromise the stability of the joint. When the stabilizing muscles are weakened or fatigued, a force couple can be disrupted, such as when the rotator cuff muscles are weakened or damaged. Under these conditions, compensatory kinematic mechanisms may be activated to maintain stability of the shoulder, potentially leading to an increased risk of injury.

3.2 Association of Shoulder Injury/Pain and Shoulder Function

The presence of shoulder impairments resulting in pain or injury can substantially influence shoulder mobility and stability, leading to modified kinematics. In turn this may lead to dysfunction, affecting both the ability to complete ADL's and quality of life. The phrase ADL refers to a group of basic physical abilities that require the least autonomy and independence, including eating, bathing and moving around independently (Edemekong et al., 2022). When there is impairment or dysfunction within the musculoskeletal system of the upper extremity, the ability to perform ADLs can be significantly compromised. Difficulties in reaching, gripping, lifting, or manipulating objects can hinder productivity, limit independence, and have a profound effect on overall quality of life (Edemekong et al., 2022). The presence of shoulder pathologies is also accompanied by alterations in shoulder kinematics (Lawrence et al., 2014) and muscle activation patterns (Ludewig & Cook, 2000; Reddy et al., 2000) and thus, lead to a reduction in the overall function of the shoulder.

3.2.1 Shoulder Kinematics Alterations

Individuals with shoulder pain and pathologies may adopt compensatory strategies to perform ADLs and functional motions. Compensatory strategies are alternative movement patterns or modifications in motor control that individuals develop to work around limitations or pain in the shoulder. These strategies aim to minimize discomfort and maximize functionality in performing tasks. Compensatory strategies can involve changes in body positioning or altered movement patterns to compensate for the impaired shoulder function (Liu et al., 2013). A frequently observed example of compensatory mechanisms employed in response to impaired shoulder function involves the compromised shoulder rhythm – the proportion of scapular upward/downward rotation compared to the elevation of the GH joint. Reduced TH and GH elevation have been observed in the presence of rotator cuff tears (RCTs) compared to non-injured shoulders (Kolk et al., 2017; Roren et al., 2012). Additionally, several studies have consistently reported abnormal scapular kinematics in individuals with RCTs, with a predominant finding of increased scapular lateral rotation observed (Kolk et al., 2017; Mell et al., 2005; Miura et al., 2017; Roren et al., 2012). Moreover, as pain levels and the size of rotator cuff tear increases, greater reliance on scapular involvement in elevating the humerus was also reported (Mell et al., 2005; Scibek et al., 2009). The consistent observation of the modified shoulder rhythm underscores the significant impact of RCTs on the dynamic interaction between the scapula and the humerus, highlighting the adaptive changes that occur in response to the compromised shoulder function.

3.3 Shoulder Function Assessment

The functionality of the shoulder is essential for carrying out a diverse range of activities that are crucial for independent living. The World Health Organization used the ADL as a main indicator for evaluating individuals' physical capabilities, functional status, and their ability to engage in self-care for independent living (*International Classification of Functioning, Disability and Health (ICF)*, n.d.). Measurement of shoulder function and motion in performing ADLs is thus imperative, as it can help determine potential shoulder function decline and prevent further loss of shoulder ability to perform ADLs independently. However, measurement of ADLs can take many forms.

One common, and accessible approach in evaluating shoulder functional outcomes is the use of questionnaire-based measures. Examples of widely used patient-perceived rating include the Oxford Shoulder Score (OSS), The Simple Shoulder Test (SST) (Roh, 2013) and the Western Ontario Rotator Cuff (WORC) index. These measures provide validated and standardized scoring systems that indicate patient perception of shoulder functionality (Roh, 2013). Specifically, these questionnaires use the psychophysical scale, which is a method that can provide information about individuals' experience and perception that may be impossible to measure physically or physiologically (Borg, 1982). Given the shoulder's large ROM and its important role in daily living movement tasks, shoulder functional self-report ratings help clinical professionals determine individuals' perceived health related quality of life, particularly, patients with shoulder disorders, both before and after surgical intervention (Wylie, 2014).

Objective and quantitative biomechanical assessment methods are gaining popularity in evaluating shoulder functionality in dynamic functional daily tasks. Advanced technologies, such as three-dimensional motion capture systems offer opportunities to directly measure shoulder ROM, three-dimensional joint kinematics, and movement coordination (Bernardina et al., n.d.; Franovic et al., 2020; Longo et al., 2022). These approaches provide more detail on individual and population-level shoulder function for various upper extremity tasks. In the context of performing ADLs, they provide a valuable opportunity to gain a deeper understanding of the normal and impaired shoulder profile in ADLs. Biomechanical assessments not only allow for the examination of the specific challenges individuals face but also provides insight into specific underlying muscular and kinematic compensations when shoulder disorders are present.

The scapula poses a unique problem for motion capture, as it moves under the skin. While multiple kinematic approaches have been used to track the scapula, the surface-based method utilizing the acromion marker cluster (AMC) is currently the most widely used (Richardson et al., 2016). Previous studies have identified skin artifact errors related to the use of the AMC, particularly at humerus elevation angles above 120 degrees. However, its non-invasive, lightweight, and accessible nature make it a feasible option for measuring ST kinematics (Karduna et al., 2001; van Andel et al., 2009). The AMC consists of a cluster of three markers attached to the posteriolateral acromion (Figure 7). During the calibration process, the AMC method captures the position and orientation between the AMC markers and the scapula. The recorded motion data, combined with the static calibration information, is then utilized to compute the scapula's orientation throughout each phase of the movement (Lang et al., 2022; MacLean et al., 2014; Richardson et al., 2016; van Andel et al., 2009).

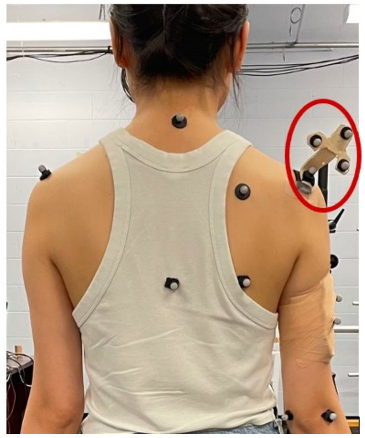


Figure 7. *The three-marker acromion marker cluster, highlighted by the red circle*

3.4 Shoulder Functional Tasks Selection

The extensive ROM and structural complexity at the shoulder introduce challenges when it comes to accurately measuring and interpreting shoulder function. Unlike the lower extremity assessment, which has a well-established and standardized assessment method in walking gait analysis, there is currently no universally accepted standardized functional assessment for the upper limb (Winter, 2009). While there are standardized assessments available for certain aspects of shoulder function, such as ROM or strength, they may not capture the full spectrum of an individual's shoulder functional abilities (Michener et al., 2002; Richards et al., 1994). Thus, the selection of shoulder functional tasks for assessment becomes crucial to obtain a more comprehensive understanding of shoulder function and its impact on ADLs.

The choice of shoulder functional task for assessment should be grounded in several considerations. These include covering the full spectrum of movements (ROM), incorporating goal-oriented movements, allowing for ease of use, and being relevant to daily functional activities and specific disorders (Friesen et al., 2023; Valevicius et al., 2018). This allows for a full assessment of function, and the impact of specific disorders or shoulder conditions on an individual's ability to carry out essential tasks (Friesen et al., 2023).

Shoulder functional tasks can be selected and examined based on the dominant planar motion required to complete the task. In the Work-Related Activities and Functional Task (WRAFT) protocol developed by Friesen et al. (2023), functional tasks were grouped into categories based on whether humerus elevation was included, which provides a structured approach to evaluating shoulder function across different degrees of freedom and functional demands. Elevation-based tasks include movements that require overhead reaching, combing hair, and throwing. These activities are common in daily life and many occupations, such as painting, high-shelf stocking, manufacturing, and sports such as swimming and baseball. Non-elevation-based tasks such as apron tying, side reach, and peroneal care also play an important role in ADL functional assessment, and are common in personal care, occupations that require manual handling, and tool manipulating. ADLs that encompass humeral axial rotations should also be considered for inclusion within the spectrum of shoulder functional tasks, because ADL tasks such as tucking a shirt, and washing the back all require the coordinated rotation of the humerus. Further, patients with RCTs consistently exhibit challenges when attempting movements that involve humeral rotations (Bruttel et al., 2019; Friesen et al., 2023; Maciukiewicz et al., 2022; Valevicius et al., 2018; C. J. van Andel et al., 2008). As a result, it is essential to incorporate an elevation task like combing hair (hand to head task) and a non-elevation axial rotation task such as tying an apron (hand to back task) in any ADL assessment of shoulder function.

Additionally, the inclusion of lifting tasks is necessary within shoulder functional assessment. Lifting tasks align with everyday scenarios that demand the ability to exert force to raise items, such as picking up groceries, lifting bags, or moving objects around. Moreover, previous studies have indicated specific challenges faced by individuals with musculoskeletal disorders in relation to lifting above and below waist height movements (Friesen et al., 2023; Friesen & Lang, 2022; Lang et al., 2019).

3.5 Shoulder Biomechanics Reliability

A few studies have addressed the reliability of 3D shoulder kinematics measures of scapular or humeral rotations. Studies involving healthy participants, reported reliability ranges from poor to excellent (Bet-Or et al., 2017; Engdahl & Gates, 2018; Friesen et al., 2023; Roren et al., 2013; Roy et al., 2007; Thigpen et al., 2005; van Andel et al., 2009; van den Noort et al., 2014; Yildiz et al., 2020). Studies involving individuals with shoulder disorders have shown moderate to excellent inter-day reliability (Haik et al., 2014; Hansen et al., 2019; Michener et al., 2016; Roy et al., 2007).

The existing reliability literature predominantly emphasizes the examination of scapular kinematic measurements among the healthy population (Bet-Or et al., 2017; Karduna et al., 2001; Meskers et al., 2007; Roren et al., 2013; Roy et al., 2007; Thigpen et al., 2005; van Andel et al., 2009; van den Noort et al., 2014; Yildiz et al., 2020), with only a limited number of studies addressing the quantification of humeral rotations (Engdahl & Gates, 2018; Friesen et al., 2023). Furthermore, the majority of current studies quantifying shoulder kinematics have focused on movements restricted to a single plane, such as arm elevation in the sagittal or frontal plane. For scapular reliability, scapular protraction exhibits weaker consistency compared to other scapular rotations, even in the resting position (Meskers et al., 2007; van Andel et al., 2009), and scapular kinematics during elevation in the sagittal plane demonstrate superior reliability compared to movements in other planes (Thigpen et al., 2005). It is crucial to note that these studies have often sought to assess reliability during highly controlled and constrained movements, which may not replicate the dynamic and multidirectional nature of shoulder functional tasks in real-life applications.

Three reliability studies have been identified that involve ADLs in the context of shoulder kinematics (Engdahl & Gates, 2018; Friesen et al., 2023; Roren et al., 2013). Engdahl & Gates (2018) quantified humeral kinematics during relatively unconstrained below shoulder height daily movements, such as turning a doorknob. In this investigation, participants were given minimal specific instructions, with the sole requirement being to return to their initial position. The results revealed excellent reliability, as indicated by averaged intraclass correlation coefficients (ICCs) ranging from 0.83 to 0.88. In a separate study conducted by Friesen et al. (2023), involving entirely different movement tasks across various ADLs, a broader range of ICCs was observed, spanning from 0.23 to 0.89 (poor to excellent) in the quantification of humeral rotations. The difference in ICCs between the two studies highlights the potential impact of diversity in task characteristics on the reliability of shoulder kinematics.

For scapular kinematic reliability studies, findings indicate that elevation-based ADLs demonstrate comparable reliability with single-plane movements (Friesen et al., 2023a; Roren et al., 2013). However, there are notable discrepancies between studies in terms of the reported ICCs. Roren et al. (2013) reported a higher range of ICCs with good to excellent reliability of scapulothoracic angles during combing task. In contrast, another study reported a much wider and weaker range of ICCs (Friesen et al., 2023). This disparity could be attributed to differences in task instructions provided to participants. Efforts were made to decrease movement variability by precisely describing and demonstrating each movement before recording in Roren et al. (2013)'s study, while only brief demonstrations and instructions were provided by Friesen et al. (2023), with an emphasis on encouraging participants to perform movements in a natural manner.

For non-elevation-based movements, both studies examining scapular kinematics concur that scapular kinematics reliability is generally weaker compared to elevation-based movements. This discrepancy may be attributed to the inherent characteristics of non-elevation-based movements, which often involve a larger range of horizontal movement and scapular retraction/protraction. Previous studies have consistently shown that scapular protraction and horizonal movement exhibits the lowest reliability and highest errors among scapular kinematics (Friesen et al., 2023; Meskers et al., 2007; C. van Andel et al., 2009). Another potential explanation for the observed phenomenon could be related to the development and familiarity of motor patterns associated with elevation-based tasks compared to non-elevation tasks. It is possible that motor patterns involved in elevation-based tasks, particularly movement in front of the body, may be more practiced. In contrast, non-elevation tasks, such as tying an apron or washing one's back, may be less commonly practiced and lack visual control. Consequently, individuals may have less developed motor patterns and may exhibit greater variability in their execution of these tasks (Friesen et al., 2023; Roren et al., 2013).

Errors in measuring kinematics can significantly impact the reliability of research findings as well. Accurate marker placement is crucial in surface-based kinematic measurements. Failure to accurately identify targeted landmarks for marker placement can lead to difficulties in defining the local coordinate system, thereby compromising the accuracy of motion analysis (de Groot, 1997; Johnson et al., 1993; Roren et al., 2013). Additionally, scapular palpation may pose even more challenges, particularly in individuals with redundant soft tissues, which can further diminish reliability (Friesen et al., 2023; Haik et al., 2014; Johnson et al., 1993).

Single-plane movements, and those with detailed instructions and demonstrations, exhibit relatively higher shoulder kinematics reliability. These types of movements typically involve controlled and constrained motions, allowing for more accurate and consistent measurements. In contrast, the reliability of ADLs tends to be lower than that of isolated-plane movements. The complex nature of ADLs, which entail multi-planar movements with several degrees of freedom, make exact repetition challenging (Roren et al., 2013). The greater variability inherent in ADLs underscores the importance of considering task complexity and contextual factors when evaluating the reliability of shoulder kinematic measurements. ADLs also serve as crucial representations of true, multiplanar shoulder function, underlining their significance in clinical evaluation and rehabilitation settings.

3.6 Inconsistency in Shoulder ADL Research

Several studies have conducted laboratory-based evaluations of shoulder kinematics of ADLs (Friesen et al., 2023; Gates et al., 2016, 2016; Magermans et al., 2005; Petuskey et al., 2007; Rab et al., 2002; Rundquist et al., 2009; Sheikhzadeh et al., 2008; C. J. van Andel et al., 2008; Vanezis et al., 2015). However, these studies have showed noteworthy disparities within their reported outcomes, underscoring the presence of inconsistencies in shoulder biomechanical protocols. These inconsistencies arise due to various factors, including lack of standardized task protocols, differences in participant populations, variations in selection of tasks, varying modeling approaches, and diverse rotation sequences used for calculating joint angles. Tables detailing the kinematic comparisons of different studies for generalized hand-to-back (non-elevation axial rotation-based tasks) and hand-to-head tasks (elevation-based tasks), can be found in Appendix F and G. Shoulder assessments lack a standardized approach, unlike the well-established gait analysis used for lower limb analysis (Friesen et al., 2023). A lack of a standardized testing protocol stands as the primary factor contributing to the notable inconsistencies across studies in the current reported outcomes of shoulder kinematics during ADLs (Appendix F and G).

One notable challenge in this area of research is the lack of consistency in the choice of functional tasks to assess shoulder functions. While some studies opt for a limited number of tasks, others choose a more comprehensive approach to ensure a broader representation of the functional movements commonly encountered in daily life (Andel et al, 2008; Gates et al, 2016; Vanezis et al, 2015). Due to the lack of standardized selection of functional tasks in assessing upper limb motions, even when researchers attempt to quantify similar movements such as a generalized hand-to-back motion, significant disparities persist in the reported outcomes. Common ADL tasks involving a hand-to-back motion encompass washing the back, peroneal care, reaching for the back pocket, and tying an apron. As an example, in the task of tying an apron (Friesen et al., 2023), a significantly higher peak TH elevation was observed compared to the task of hand to the ipsilateral back pocket (Petuskey et al., 2007; van Andel et al., 2008; Vanezis et al., 2015). This discrepancy arises because the tying an apron task necessitates extending the reach toward the middle of the back, demanding a greater degree of TH elevation compared to tasks involving the hand-to-ipsilateral back pocket motion. The inclusion of different functional tasks in previous studies, representing the same generalized movement pattern at the shoulder, introduces challenges in making cross-study comparisons.

When researchers select a similar set of representative ADL tasks, variations in the instructions provided to participants can also result in divergent findings. Differences in instructions, or even the absence of specific instructions, can introduce variability in how participants perform the tasks. This variability can arise from variations in movement speed, starting and ending positions, technique, or other factors that influence the execution of the tasks. These differences can significantly influence the performance and kinematics of the selected tasks, ultimately affecting the outcomes of the study (Sheikhzadeh et al., 2008). In some studies, researchers may provide detailed instructions and demonstrations (Gates et al., 2016; van Andel et al., 2008), specifying the desired movement patterns, speed, or other parameters. This approach aims to standardize the execution of the tasks and minimize interparticipant variability but can introduce too many task constraints to represent true ADLs. Conversely, other studies may provide minimal instructions, allowing participants to perform the tasks according to their own interpretation and habitual patterns (Rab et al., 2002; Petuskey et al., 2007). This more flexible approach acknowledges the natural variability in ADLs, but can result in a wider range of movement strategies and kinematic outcomes. To enhance the generalizability and facilitate the comparison of kinematic outcomes across studies, the protocol should provide the participant with standardized initiation and finishing task instructions. However, it is equally crucial that the protocol does not overly constrain the movements in terms of plane of motion, range of motion, or speed (Friesen et al. 2023). By preserving a degree of flexibility, the protocol accommodates individualized task execution styles, mirroring real-world scenarios and offering practical applicability.

The variability in study populations adds another layer of complexity to the comparison of shoulder kinematic outcomes across studies. Some investigations specifically focused on adolescents (Petuskey et al., 2007; Rab et al., 2002; Vanezis et al., 2015), while others recruited a wide age range of adults (Friesen et al., 2023; Gates et al., 2016; Magermans et al., 2005; Rundquist et al., 2009; van Andel et al., 2008). This variation in age groups is noteworthy because age is known to be a risk factor for shoulder disorders and can potentially influence shoulder kinematics outcomes (C. J. Hodgetts et al., 2021). The physiological changes and potential limitations associated with aging may impact joint mobility, muscle strength, and overall movement patterns and muscle recruitment strategies during ADLs (Morrison & Newell, 2012). Consequently, the inclusion of different age groups within studies introduces a confounding factor that contributes to the variability in kinematic findings.

Another factor that can significantly influence shoulder kinematics outcomes is the choice of kinematic modeling. Different rotation sequences utilized for calculating joint angles can lead to significantly different outcome measures. The International Society of Biomechanics (ISB) guidelines provide standardized recommendations for defining anatomical reference frames and rotation sequences when calculating joint angles. However, gimbal lock can occur in TH and GH kinematic calculations when utilizing the ISB recommended YXY rotation sequences (Wu et al., 2005) when the humerus elevates to 0 and 180 degrees (Doorenbosch et al., 2003). Therefore, to address this, it is necessary to consider alternative rotation sequences within the specific testing protocol to combat gimbal lock. One suggested approach to mitigate gimbal lock is to utilize the XZY sequence for movements primarily in the frontal plane and the ZXY sequence for movements mostly in the sagittal plane (Kontaxis et al., 2009). By systematically incorporating the alternative rotation sequences, researchers can reduce the occurrence of gimbal lock, and enhance consistency and comparability of kinematic outcomes between studies.

3.7 Conclusion

The shoulder is a complex structure that plays a crucial role in facilitating upper limb movement and function. However, there is a significant prevalence of shoulder disorders and pain, which can result in compensatory biomechanics, adverse shoulder function and poorer quality of life. Given the high prevalence of these issues, it becomes increasingly important to assess and understand biomechanical shoulder function comprehensively.

There are discrepancies in current research regarding shoulder kinematics in healthy individuals during dynamic movements. These inconsistencies can be attributed to various methodological factors, such as the lack of standardization in testing protocols and methodologies, distinctions in task selections, task descriptions and instructions, and rotation sequences. This hinders the establishment of a clear and comprehensive understanding of fundamental shoulder function, comparison of research across different studies and development of effective clinical treatments.

To address this research gap and advance our knowledge of shoulder function, there is a need for a comprehensive, standardized assessment of shoulder kinematics. This assessment should encompass not only planar movements of the shoulder but also the closed-chain interplay involved in ADLs throughout the ROM of the shoulder.

Furthermore, the protocol should encompass standardized instructions to facilitate consistent and replicable test results, thereby enabling comparisons in future studies. The study population should predominantly comprise healthy participants. Investigating shoulder movement patterns within an uninjured cohort during ADLs offers valuable insights into deviations observed in individuals with musculoskeletal conditions or the aging shoulder. Such normative data can be employed to establish meaningful reference points and guide clinical assessments and interventions.

CHAPTER 4. METHODS

To achieve the expressed purpose of this study, young and healthy participants completed five standardized shoulder function tasks during two testing sessions separated by a maximum of 2 weeks. During both sessions, three-dimensional motion capture was collected to assess scapular-thoracic and GH kinematics. Intra-class correlation coefficients (ICCs), standard error of measurement (SEM), and minimal detectable change (MDC) were used to assess differences in between-session joint angles.

4.1 Participants

4.1.1 Recruitment

Participants between 18 – 30 years old with no history of shoulder pain or injury were recruited from Halifax, Nova Scotia. As one of the purposes of this study was to quantify values for healthy shoulder biomechanics, the age of participants was restricted (18 – 30 years old) as functional impairments related to age and risk of shoulder tendinopathy increase after the age of 30 (Imhoff & Savoie, 2019). All study protocol and consent forms were reviewed and approved by the Dalhousie University Research Ethics Board (REB # 2022-6397).

4.1.2 Inclusion and Exclusion Criteria

Inclusion criteria encompassed individuals aged 18 to 30 years, with no history of shoulder injury or shoulder pain. Exclusion criteria included individuals answered “yes” to any of the conditions in the Musculo-Skeletal Health Screening questions section (Appendix D) and had a score of < 90% on the total Western Ontario Rotator Cuff (WORC) scores (Appendix E).

4.2 Experimental Design

Before the first visit to the lab, participants were asked to complete the Musculo-Skeletal Health Screening questionnaire (Appendix D) and the Western Ontario Rotator Cuff (WORC) questionnaire (Appendix E). These questionnaires inquired about potential symptoms, signs and functional limitations associated with rotator cuff tendinopathy. The WORC was used as a screening tool in the study; participants who scored < 90% would be excluded from the study.

The study took place at the Dalhousie Kinesiology Department in the Biomechanics Ergonomics Neuroscience (BEN) research lab (Dalplex 217). This study involved 2 test sessions for each participant. Upon arrival in the BENlab, participants were acquainted with the research team and study equipment. Following this, participants were reminded of the study rationale, purpose, and methodology, and then the risks of the study protocols were reviewed. They were given time to review the letter of consent (Appendix A) and ask any questions they may have. Following this review, participants signed the informed consent form. Participants were also asked to wear tight-fitting tank-top, to ensure accurate marker placement.

After consent was collected and all questions were answered, the participant underwent descriptive measurements. A stadiometer and a balance scale were used to measure the participants' height and weight. The participants' age, sex, and operational hand (the hand primarily used for manual tasks) were also recorded, so the researcher could determine descriptive data based on the population that would partake in the study. Following these measures, the three-dimensional motion capture protocol examining ADLs was initiated.

Participants returned to the lab for a re-test session between 3-days to 2-weeks from their initial test session. The second, re-test session took place at approximately the same time of day as the first test session. At both study visits, the participants underwent the same 3D motion capture protocol to measure kinematics. Both test sessions consisted of equipment set-up, followed by performance of a series of functional tasks. Each test session took approximately 2 hours. Figure 8 illustrates the experimental design of the study, detailing the procedures to be undertaken during both test sessions.

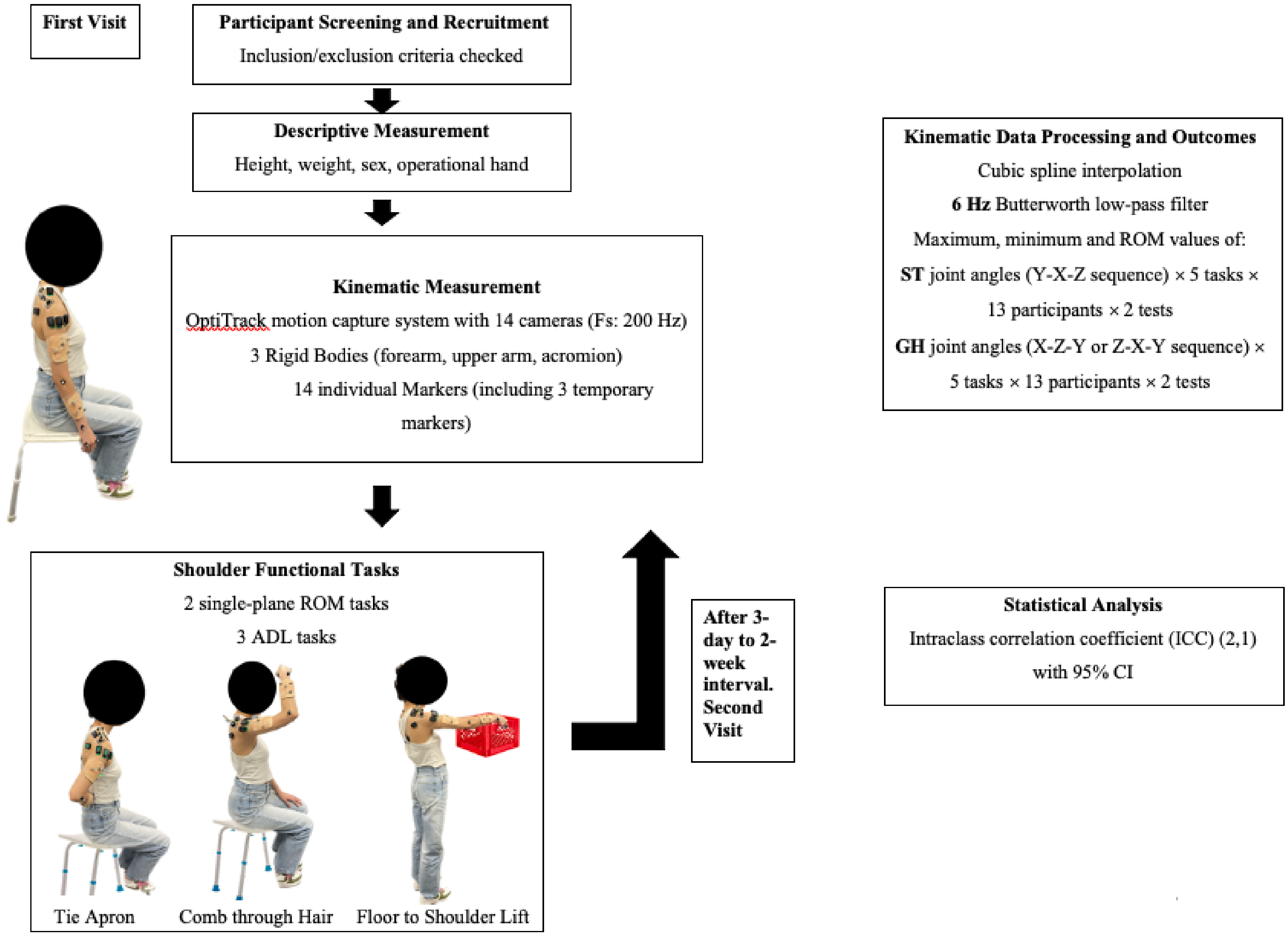


Figure 8. *Experimental design flowchart.*

4.2.1 Kinematic Measurement

Kinematic analyses of unilateral upper extremity movements were tracked with fourteen optoelectronic motion capture cameras (OptiTrack NaturalPoint Inc., Corvallis, Oregon, USA) and retroreflective markers at a sampling frequency of 200 Hz. One camera from the motion capture system was set to video mode to confirm the upper extremity and thorax movement trajectories, while the remaining thirteen cameras captured markers' position data. Video recording would not occur before or between trials, and there would be no audio recording during the experiments. Motive software (version 2.1.1, NaturalPoint, Inc., Oregon, USA) was used for data acquisition and marker labelling.

Eleven individual passive reflective markers were affixed with double-sided adhesive tape on the following anatomical landmarks on the participants' operation hand side: seventh cervical vertebra spinous process (C7), eighth thoracic vertebra spinous process (T8), suprasternal notch (IJ), xyphoid process (PX), the acromion angle on the non-operational hand side (AA), medial and lateral epicondyles (EM and EL), ulnar and radial styloids (US and RS) and second (MCP2) and fifth metacarpophalangeals (MCP5) (Figure 9).

To track dynamic scapular motion, the AMC method was used. A marker cluster that consists of three non-collinear markers fixed to a rigid body was placed on the participant's dominant side of the flat part of the acromion (MacLean et al., 2014), and 3 temporary markers were placed on operational hand side AA, root of the spine (TS) and the inferior angle (AI) (Friesen et al., 2023; Wu et al., 2005). Two additional marker clusters consisting of four non-collinear markers affixed to rigid plates were placed on the upper arm and forearm unilaterally. The AMC is shown as a solid triangle. Other rigid marker clusters are shown as rectangles. Individual markers are indicated by red dots. Temporary scapular markers are indicated with X's. Kinematic data were collected unilaterally on all participants (Figure 9).

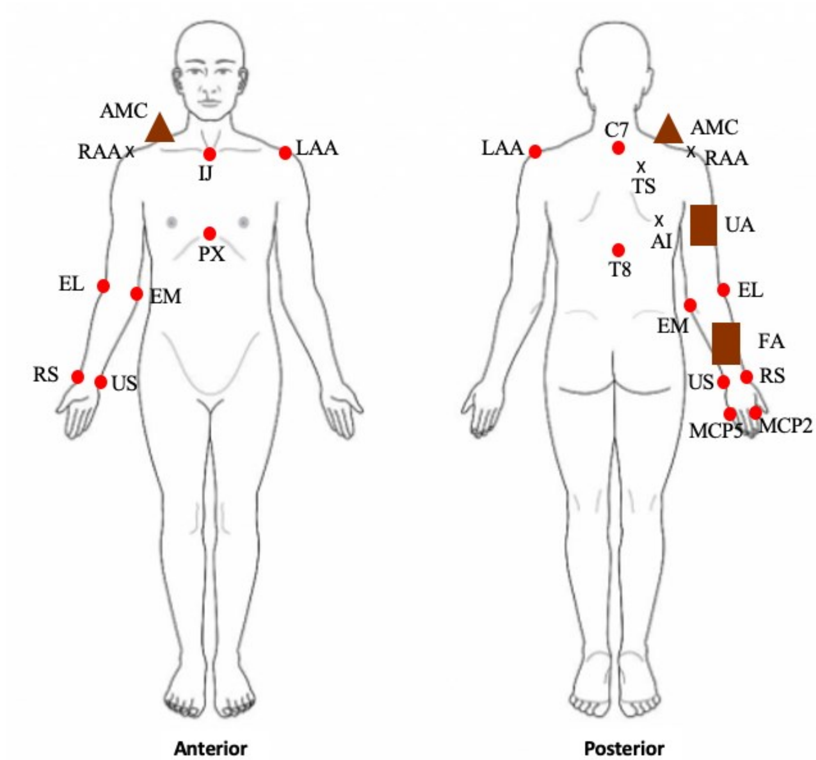


Figure 9. *Anterior and posterior view of markers placement. AMC = Acromion marker cluster; UA = Upper arm rigid body marker cluster; FA = Forearm rigid body marker cluster; RAA/LAA = Right/left Angulus Acromialis (acromion angle); TS = Trigonum Spinae Scapulae (root of the spine); AI = Angulus Inferior (inferior angle); IJ = Deepest point of Incisura Jugularis (suprasternal notch); PX = Processus Xiphoideus (xiphoid process); C7 = Processus Spinosus of the 7^{th} cervical vertebra; T8 = Processus Spinosus of the 8^{th} thoracic vertebra; EL/EM = Most caudal point on lateral/medial epicondyle; RS = Most caudal-lateral point on the radial styloid; US = Most caudal-medial point on the ulnar styloid; MCP2 = 2^{nd} metacarpophalangeal; MCP5 = 5^{th} metacarpophalangeal.*

4.2.2 Calibration and Shoulder Functional Tasks

Before performing the upper limb tasks, a static calibration trial was carried out, with the participant standing quietly in anatomical position for 5 seconds (Figure 10). After this trial, the three temporary markers on participants' scapula (operational side AA, TS and AI) (Figure 10: red circle) were removed.

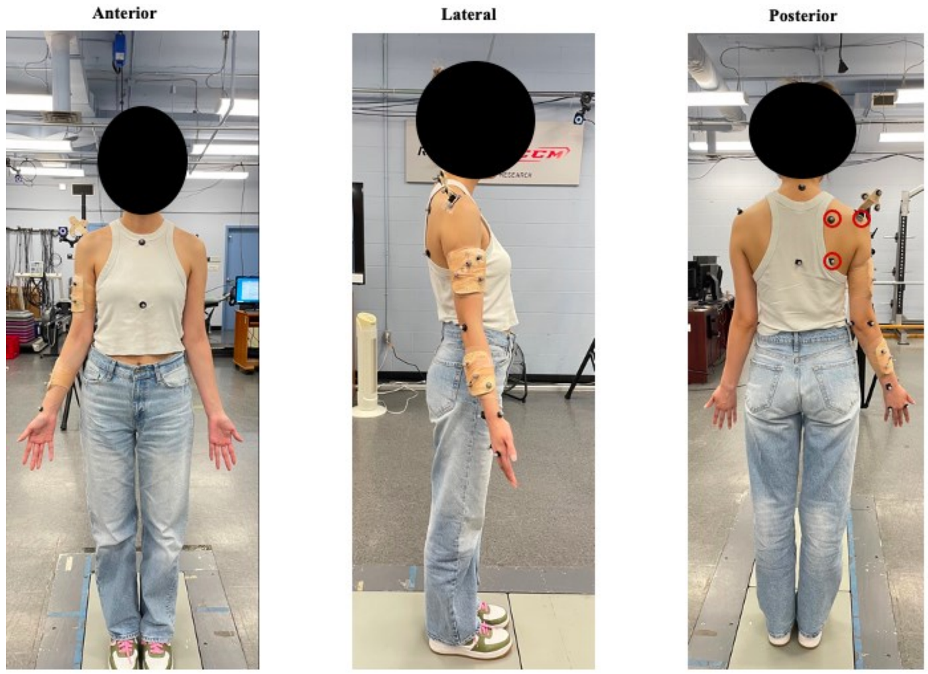


Figure 10. *Marker set in the calibration trial, including the AMC marker cluster affixed to the posterolateral acromion.*

Following calibration, the experimental protocol consisting of two single-plane arm maximum elevation movements in the frontal and sagittal planes and three different daily living functional task were tested (Table 1). The order of the tasks was randomized. Participants executed five consecutive repetitions of each task, with a 5-second break provided between each repetition. Participants were given rest between each task, as needed. For the two single-plane ROM tests (Table 1), the participant started in a seated position on a stool, ensuring their back remains still. Their arms were positioned by their sides. At the end of a countdown, they were instructed to raise their arms as high as possible, in front of the body (flexion) or to the side (abduction). The functional tasks encompassed three goal-oriented activities commonly encountered in daily life, involving a variety of available ROM and rotations. Participants received standardized instructions for starting and finishing the task, and a brief demonstration, but they were encouraged to perform the tasks in a natural manner. These instructions are provided in Table 1.

Table 1.Different shoulder functional movement tasks

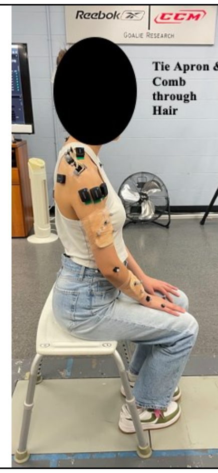
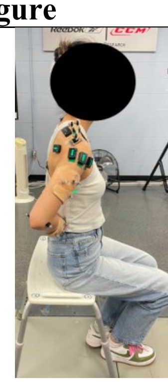
Starting Positions for Different Tasks	 	
ROM Task	**Description**	
Flexion Maximum range of motion	Description: Participants are instructed to maintain a seated position on a stool throughout the task. Instruction: Arm hanging by side with palm facing inward, raise the arm in front of the body as high as possible. Once at maximum, then lower the arm back to the starting position.	
Abduction Maximum range of motion	Description: Participants are instructed to maintain a seated position on a stool throughout the task. Instruction: Arms hanging by side with palm facing inward, elevate the arm at the side of the body as high as possible. Once at maximum, then lower the arm back to the starting position.	
ADL Task	**Description**	**Figure**
Tie Apron	Description: Participants are instructed to maintain a seated position on a stool throughout the task. Instruction: Start with palm of each hand resting on the same-side thigh. Move the back of both hands (dorsal side) behind the back at waist-level, such that the backside of the hand is directed forward, and palm-side is facing backward. Once the hands are in this position, simulate the act of tying an apron at the midback, then return to the starting position.	

Table 1. *Different shoulder functional movement tasks*

ADL Task	Description	Figure
Comb through hair	Description: Participants are instructed to maintain a seated position on a stool throughout the task. Instruction: Start with palm of the operational hand resting on the top of the same-side thigh. With a comb in operational hand, reach to the start of the hairline, and simulate combing the hair from the front hairline down to the end of the hairline at back of the head (right below the occipital area). Then return to the starting position	
Floor to Shoulder Lift	Description: To ensure consistent positioning, the shoulder height was aligned with the participant's horizontally held arms. This alignment was achieved by adjusting the bolt height of a tripod to match the participant's shoulder level before starting the task. Instruction: While standing in front of the milk crate with 1kg load in a neutral position, bend down to reach and grasp the handles of the milk crate firmly with both hands. Lift the milk crate box off the floor, and continue to raise the crate in an upward motion until the handles align with the shoulder height and arms are parallel with the floor. Pause briefly, ensure a stable grip and body position, then lower the crate back to the floor until safely placing the crate on the floor. Return to the starting position.	

4.3 Kinematic Data Processing

Kinematic data were processed using custom MATLAB scripts. Missing data points in the raw kinematic data were effectively handled by employing the spline function. Then the trajectories data were dual-pass filtered with a 4th order Butterworth low-pass filter at a cut-off frequency of 6 Hz (Winter, 2009). The filtered data were utilized to establish segment coordinate systems for each segment. Joint coordinate systems were used to describe relevant rotations at the joints.

4.3.1 Segment Coordinate System

Three body segments were included in the kinematic model: scapula, upper arm, and thorax. Each body segment was assumed as a rigid body. The scapula was defined by the TS, AA and the AI markers. The thorax segment was defined by the C7, T8, IJ and PX markers. The upper arm was defined by the EM and EL markers and GH joint center. The estimation of the GH joint center was achieved using an equation. According to this equation, the GH joint center is located inferiorly relative to the AA and at a point that is 17% of the distance between the right and left AA from the axial direction (Rab et al., 2002). The origin and coordinate system of each segment was created using 3D marker trajectories (Wu et al., 2005). The definition of a segment's local coordinate system involved the utilization of three noncolinear points. Like the global coordinate system (GCS) depicted in the Figure 11, the local coordinate system (LCS) adheres to a right-handed and orthogonal structure. The orientation of the segment's LCS was established: the Y-axis aligned superiorly, the X-axis pointed anteriorly, and the Z-axis directed laterally to the participant's right. This LCS orientation was applied to the thorax, upper arm, and scapula and adhered to the ISB guidelines.

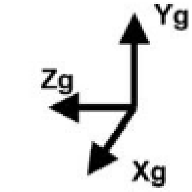


Figure 11. *Global coordinate system definition (Wu et al., 2005)*

i. *Thorax.* The origin of the thorax (O*t*: IJx, IJy, IJz) was defined as IJ. The coordinate system was defined as suggested by ISB guidelines. The Y component of the thorax LCS (Yt) was defined by the line connecting the midpoint between PX and T8 and the midpoint between IJ and C7, pointing upward.

$$Yt = \frac{\frac{(C7+IJ)}{2} - \frac{T8+PX}{2}}{\left|\frac{(C7+IJ)}{2} - \frac{T8+PX}{2}\right|}$$

The Z component of the thorax (Zt) was perpendicular to the plane that is formed by IJ, C7 and midpoint between T8 and PX, pointing to the right.

$$Xtemporary = \frac{IJ-(IJ+C7)/2}{\left|IJ-\frac{IJ+C7}{2}\right|}$$

$$Zt = \frac{Yt \times Xtemporary}{|Yt \times Xtemporary|} \text{ (×: cross product)}$$

While the X component of the thorax (Xt) was the line perpendicular to both Yt- and Zt-axis, pointing forward (Wu et al., 2005).

$$Xt = \frac{Yt \times Zt}{|Yt \times Zt|}$$

ii. *Upper arm.* Based on the ISB guidelines, the upper arm origin was located at GH joint center (O_{UA}: GHx, GHy, GHz). The Y component of the upper arm (Y_{UA}) was defined as the line connecting GH and midpoint of the EL and EM.

$$Y_{UA} = \frac{GH-(LE+EM)/2}{\left|GH-\frac{LE+EM}{2}\right|}$$

The X component of the upper arm (X_{UA}) was defined by the line perpendicular to the plane formed by EM, EL and GH, pointing forward.

$$Ztemporary = \frac{EM-(EM+EL)/2}{|EM-(EM+EL)/2|}$$

$$X_{UA} = \frac{Yh \times Ztemporary}{|Yh \times Ztemporary|}$$

The Z component of the upper arm (Z_{UA}) was defined as the line perpendicular to both - Y_{UA} and X_{UA}: axis (Wu et al., 2005) (see Figure 12).

$$Z_{UA} = \frac{Yh \times Xh}{|Yh \times Xh|}$$

iii. Scapula. The origin of the scapula was defined with AA (Os: AAx, AAy, AAz). The Z component of the scapula LCS (Zs) was defined as the line connecting TS and AA, pointing to AA.

$$Zs = \frac{AA - TS}{|AA - TS|}$$

The X component of the scapula LCS (Xs) was the line perpendicular to the plane formed AI, AA and TS, pointing forward.

$$Ytemporary = \frac{AI - TS}{|AI - TS|}$$

$$Xs = \frac{Zs \times Ytemporary}{|Zs \times Ytemporary|}$$

The Y component of the scapula (Ys) was the common line perpendicular to the Xs-and Zs-axis, pointing upward (Wu et al., 2005) (see Figure 12).

$$Ys = \frac{Zs \times XS}{|Zs \times XS|}$$

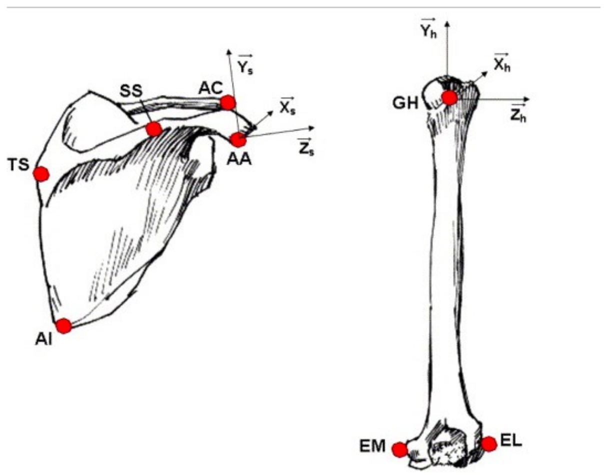


Figure 12. *Bone landmarks and local coordinate systems of humerus and scapula (Šenk & Chèze, 2006).*

4.3.2 Joint Rotations

To describe the motion of shoulder joints, two types of rotations are recommended: 1) rotation of a segment relative to the proximal segment including the humerus relative to the scapula: GH joint. 2) rotation of a segment relative to the thorax: ST joint (Wu et al., 2005). 3D joint angles were calculated through calculating three consecutive rotations of the LCS of one body segment with respect to the other body segment. Cardan-Euler angles are the most commonly used method to calculate 3D joint kinematics (Valevicius et al., 2018). The ISB standardized the LCS definitions and rotation orders for upper limb kinematic analysis in 2005. In the ISB recommendations are notated with α around the Z axis (representing the sagittal plane, rotation: flexion/extension), β is around the X axis (representing the frontal plane, rotation: abduction/adduction), γ is around the Y axis (representing the transverse plane, rotation: axial rotation). The rotation matrices for a rotation about X, Y, Z axis are listed below:

$$Rx\ (\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix}$$

$$Ry\ (\gamma) = \begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$Rz\ (\alpha) = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

GH joint. To combat the issue of singularities in calculating GH rotations, Kontaxis et al. (2009) recommended using different rotation sequences depending on the predominant plane of movement. The XZY rotation sequence was employed during the maximum abduction task in this study. Additionally, based on recommendations from Friesen et al. (2023) and Schnorenberg et al. (2022), the XZY rotation sequence was utilized for the tie apron and multiplanar comb hair tasks. Conversely, the maximum flexion and floor to shoulder lift involve movements primarily in the sagittal plane. Therefore, the ZXY rotation sequence was utilized for these tasks.

For the XZY rotations around the X-, Z-, and Y-axes representing the abduction/adduction in the frontal plane (βGH), flexion/extension in the sagittal plane (αGH) and axial rotations in the transverse plane (γGH) respectively. The rotation matrix for each axis was multiplied together to create the following XZY Cardan rotation matrix:

The X-Z-Y Cardan rotation matrix = Rx (β).Rz (α).Ry (γ)

$$[R] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} . \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} \mathrm{Cos}\,\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$[R] = \begin{bmatrix} \cos\beta\cos\gamma & -\sin\beta & \cos\beta\sin\gamma \\ \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma \\ \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma \end{bmatrix}$$

For the ZXY rotations around the Z-, X-, Y- axes, representing the flexion/extension in the sagittal plane (αGH), abduction/adduction in the frontal plane (βGH), and axial rotation in the transverse plane (γGH). The rotation matrix for each axis was multipled together to create the following ZXY Cardan rotation matrix:

The Z-X-Y Cardan rotation matrix = Rz (α).Rx (β).Ry (γ)

$$[R] = \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} . \begin{bmatrix} \mathrm{Cos}\,\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix}$$

$$[R] = \begin{bmatrix} \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\sin\alpha\alpha\cos\beta & \cos\alpha\sin\gamma + \sin\alpha\sin\beta\cos\gamma \\ \sin\alpha\cos\gamma + \cos\alpha\sin\beta\sin\gamma & \cos\alpha\cos\beta & \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma \\ -\cos\beta\sin\gamma & \sin\beta & \cos\beta\cos\gamma \end{bmatrix}$$

ST functional joint. The motion of the scapula relative to the thorax was characterized by the YXZ Cardan rotation sequence following the ISB recommendations, representing protraction/retraction in the transverse plane (γST), upward/downward rotation in the frontal plane (βST), and anterior/posterior tilt in the sagittal plane respectively (αST). The rotation matrix for each axis was multiplied together to create the following YXZ Cardan rotation matrix:

The Y-X-Z Cardan rotation matrix = Ry (γ). Rx (β). Rz (α)

$$[R] = \begin{bmatrix} \cos\gamma & 0 & \sin\gamma \\ 0 & 1 & 0 \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} . \begin{bmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$[R] = \begin{bmatrix} \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \sin\alpha\cos\beta \\ \cos\beta\sin\gamma & \cos\beta\cos\gamma & -\sin\beta \\ \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \cos\alpha\cos\beta \end{bmatrix}$$

4.4 Start and End of Task

The start and end points of each trial were determined objectively using the resultant linear velocities of the hand markers. The threshold was set as 2% of the peak resultant linear velocity achieved during task performance for the hand markers (Alt Murphy et al., 2018; Murphy et al., 2006, 2011; Schnorenberg et al., 2022). The start of the task was identified by the frame in which the marker's resultant linear velocity exceeded the threshold, while the frame in which the hand marker's velocity returned to below 2% of the peak velocity was identified as the end of the task. Start and end of each trial were also visually inspected for correctness.

Once the start and end points of each trial were verified, the calculated ST and GH joint angles were time-normalized to represent 100% of the task duration. This normalization process mapped the kinematic data from 0% (start point) to 100% (end point) for each repetition. Subsequently, the time-normalized kinematic data from five repetitions of each task were averaged to obtain a representative dataset for further data analysis.

4.5 Statistical Analysis

For each task, discrete kinematic variables, including the minimum, maximum joint angles, and ROM, were computed for each rotation. Specifically, discrete variables including scapular protraction/retraction, upward/downward rotation, and anterior/posterior tilt, as well as GH abduction/adduction, flexion/extension, and internal/external rotation at peak positions, along with ST and GH ROM in different planes were calculated. For each of the five tasks, an averaged movement pattern waveform was plotted against the percentage of the task completion for ST and GH rotations.

The inter-day test-retest reliability of the ST and GH kinematic discrete variables were carried out using IBM SPSS Statistics 28 and custom MATLAB scripts.

The agreement between two test sessions for all discrete variables was assessed using the intraclass correlation coefficient (ICC). The ICC model, type, and definition were selected based on previous research (Koo and Li, 2015). For test-retest reliability measurement, a two-way mixed-effects model of ICC was applied. Although five repetitions of each task were conducted, the average of these repetitions was used to represent a single measurement. Therefore, a single-measurement type was employed. Since two identical measurements across test sessions were anticipated, absolute agreement was utilized. Consequently, a two-way mixed-effects absolute agreement ICC (2,1) with a 95% confidence interval (CI) was used to evaluate the reliability. This led to the calculation of 9 ICCs per movement plane for each task (five tasks in total), resulting in a total of 90 ICCs for each participant, encompassing both ST and GH kinematics. The ICC is a value between 0 and 1, where values below 0.4 indicate poor reliability, between 0.4 and 0.59 fair reliability, between 0.60 and 0.74 good reliability, and any value above 0.74 indicates excellent reliability (Roren et al., 2013; Shrout & Fleiss, 1979). The Bland-Altman (B&A) plots were utilized for all kinematic discrete variables to provide a visual representation of the agreement between two test sessions by plotting the difference between them against their mean, and using reference line at the mean difference and at 1.96 standard deviation (SD) of the mean difference.

The precision of the measurements for each kinematic variable was determined using standard error of measurement (SEM) and minimal detectable change (MDC). SEM (SEM = SD × $\sqrt{1 - ICC}$) was calculated using the SD and test-retest reliability coefficient, with the SD representing the variability across all subjects ($\sqrt{Sum\ of\ Squares\ Total/(n-1)}$.) SEM's independence from the specific ICC ensures consistency in interpreting SEM values across studies (Friesen et al., 2023; Weir, 2005). Moreover, SEM is regarded as an absolute index, maintaining consistency across populations and remaining impervious to between-subjects variability (Weir, 2005). MDCs were derived from SEM, with a confidence level of 95% (MDC = SEM × $\sqrt{2}$× 1.96) (Beninato & Portney, 2011; Friesen et al., 2023; Furlan & Sterr, 2018; Yildiz et al., 2020). It serves to define the minimum difference needed between separate days on a participant for the difference to be considered real (Weir, 2005; Yildiz et al., 2020).

Finally, the mean ROM for each rotation for both scapular and GH kinematics was calculated, presented in the format of average and its SD, which facilitates the comparison of differences and SDs between the two test sessions. Additionally, to visually demonstrate the qualitative comparison analysis, the mean averaged waveform for each rotation across tasks was plotted against the completion percentage of the task. This graphical representation provides a comprehensive visualization of the kinematic patterns across five movement tasks.

CHAPTER 5. RESULTS

5.1 Participant Characteristics

Data were collected on 15 healthy participants. However, upon analysis, it was discovered that the kinematics results for two participants exhibited significant gimbal locks and were subsequently excluded from the dataset. Therefore, the final analysis was conducted using data from a total of 13 participants (6 males and 7 females; 12 right-handed and 1 left-handed) (Table 2).

Table 2. *Participant characteristics*

Participant	Age (years)	Gender	Dominant Arm	Height (m)	Weight (kg)	Inter-session Interval (days)
1	25	F	R	1.69	52.9	7
2	21	F	R	1.70	60.6	4
3	22	F	R	1.61	77.0	7
4	21	F	L	1.58	52.2	7
5	24	F	R	1.69	61.7	14
6	20	M	R	1.88	93.3	13
7	25	M	R	1.70	79.5	6
8	23	M	R	1.78	62.5	5
9	21	M	R	1.68	75.4	14
10	24	M	R	1.85	90.1	7
11	22	M	R	1.66	69.0	3
12	22	F	R	1.71	67.6	3
13	22	F	R	1.55	45.5	3
Average (± 1 SD)	22.5 (±1.6)	6 M & 7 F	12 R & 1 L	1.70 (±0.10)	68.3 (±14.4)	7.2 (±4.0)

(SD=standard deviation; M=male; F=female; R=right; L=left)

5.2 Test-retest Reliability

5.2.1 Scapulothoracic Kinematics Reliability

The summary of the ST three-dimensional kinematics inter-day reliability ICC, SEM and MDC values for five movement tasks are shown in Table 3. Non-elevation-based tasks (tie apron and floor to shoulder lift) exhibited higher ICCs and lower SEM and MDC values compared to elevation-based tasks (maximum abduction, flexion, and comb through hair) for all scapular kinematics across the five movements.

For scapular protraction/retraction, the ICCs ranged from 0.136 to 0.840, while SEM ranged from 3° to 31°, and MDC ranged from 9° to 86° (Table 3). Elevation-based abduction tasks consistently displayed lower ICCs (0.166 – 0.276) and higher SEM values (14° - 31°). Similarly, the MDC for this task ranged from 38° to 86°. Conversely, non-elevation-based tasks showed good to excellent reliability, and the lowest SEM (3° - 5°) and MDC (9° - 14°) values.

For scapular upward/downward rotation, the ICCs ranged from 0.039 to 0.790, with SEM ranging from 3° to 20° and MDC ranging from 8° to 55° (Table 3). Scapular upward/downward rotation similarly exhibited higher reliability in non-elevation-based tasks. The remaining elevation-based movements demonstrated poor to fair reliability of their discrete variables. Abduction displayed the lowest reliability, with ICCs ranging from 0.039 to 0.171, accompanied by the highest SEM (11° - 20°) and MDCs (32° - 55°). Conversely, lifting tasks demonstrated the lowest SEM (4°) and MDC (10° - 11°) values, indicating relative superior absolute reliability.

Regarding scapular anterior/posterior tilt, the ICCs ranged from 0.111 to 0.789. SEM varied from 2° to 40°, while MDC ranged from 7° to 110° (Table 3). The tie apron task exhibited ICCs ranging from 0.664 to 0.722, indicating good to excellent reliability across all variables. Additionally, they demonstrated the lowest SEM (2° - 3°) values and consequently, MDCs (7° - 10°). In contrast, the comb and lift tasks displayed fair to good (ICC: 0.468 – 0.648) and fair to excellent reliability (ICC:0.465 – 0.789), respectively. Flexion movements showed variable reliability across discrete measurements, with the minimum joint angle demonstrating poor reliability (ICC: 0.111), and excellent reliability observed for maximum joint angle (ICC: 0.749) and ROM (ICC: 0.762), respectively. Despite the low ICC value for flexion minimum joint angle, the low SEM (8°) of this variable indicates that the variability in measurements is also relatively low, which contributes to its absolute reliability. The abduction task consistently exhibited relatively low reliability, ranging from poor to fair reliability (ICC: 0.213 - 0.564), accompanied by the highest SEM (5° - 40°) and MDCs (15° - 110°).

Bland-Altman plots, which depict the difference between two test sessions against the average of the two test sessions, were generated for the ST rotations in each of the five tasks. These plots can be found in Appendix H. Bland-Altman plots provide a visual check of the ST kinematics agreement between measurements obtained from two test sessions.

Table 3. *Test-retest reliability of the scapulothoracic kinematics analyses*

	Task 1: Abduction			Task 2: Tie Apron			Task3: Comb through Hair			Task4: Flexion			Task5: Floor to Shoulder Lift		
Scapular Protraction/Retraction	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.276	14	38	0.628	4	12	0.413	7	20	0.774	5	14	0.663	4	11
Maximum	0.136	31	86	0.652	4	12	0.576	8	21	0.618	12	33	0.840	5	14
Range of Motion	0.166	24	65	0.712	3	9	0.554	6	17	0.525	10	28	0.838	3	9
Scapular Upward/Downward Rotation	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.039	14	38	0.494	5	15	0.238	9	25	0.443	10	28	0.790	4	11
Maximum	0.046	20	55	0.405	4	12	0.223	5	13	0.063	5	13	0.377	4	10
Range of Motion	0.171	11	32	0.786	3	8	0.239	9	24	0.614	8	22	0.616	4	11
Scapular Anterior/Posterior Tilt	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.564	5	15	0.686	3	10	0.468	4	12	0.111	8	22	0.465	4	11
Maximum	0.213	40	110	0.722	3	8	0.621	12	32	0.749	16	44	0.789	5	13
Range of Motion	0.249	37	103	0.664	2	7	0.648	10	28	0.762	14	38	0.744	4	12

5.2.2 Glenohumeral Kinematics Reliability

The summary of the GH three-dimensional kinematics inter-day reliability ICC, SEM and MDC values for five movement tasks are shown in Table 4. Significantly higher measurement precision, characterized by much lower SEM and MDCs, was observed in non-elevation-based tasks when compared to elevation-based tasks across all GH kinematics. Particularly notable was the high measurement error observed in abduction and comb tasks.

For GH abduction/adduction, the ICC ranged from -0.181 to 0.602, with SEM ranging from 4° to 40° and MDC ranging from 11° to 110°. All variables exhibited poor to fair reliability across tasks, except for the maximum variable in flexion tasks, which demonstrated good reliability with an ICC of 0.609 (Table 4). The abduction task showed low reliability along with high SEMs (8° – 40°) and consequent high MDCs (21° - 110°). However, despite the low ICCs, lift tasks exhibited the lowest SEMs across tasks, ranging from only 4° to 6°, and MDCs ranging from 11° to 18°.

For GH flexion/extension, the ICCs ranged from 0.392 to 0.831. SEM varied from 4° to 12°. MDC ranged from 12° to 32° (Table 4). Good to excellent reliability was observed across all variables for combing through hair tasks, with ICCs ranging from 0.688 – 0.831. Additionally, this task demonstrated a relatively low and stable SEM of 5° and MDCs ranging from 13° to 14°. Fair to good reliability was reported in abduction and lift tasks, however, lift tasks (6° - 7°) exhibited a better SEM compared to abduction tasks (6° - 11°). Flexion tasks exhibited greater variability in ICC outcomes across different variables, ranging from fair to excellent reliability, with SEMs and MDCs varying from 5° to 12° and 15° to 32° respectively.

For GH internal/external rotation, the ICCs ranged from -0.076 to 0.764, with SEM ranging from 6° to 34° and MDC ranging from 18° to 93° (Table 4). The lift task showcased good to excellent reliability for both peak and range values, with notable absolute reliability reflected in low SEMs ranging from 6° - 7° and MDCs (18° - 19°). Significant variability was found across discrete variables for the remaining movement tasks, all of which exhibited poor to good reliability. Additionally, abduction and comb through hair tasks demonstrated relatively high measurement errors with SEMs ranging from 11° to 34° and MDCs ranging from 31° to 93°. Despite varied ICCs, flexion and tie apron tasks exhibited considerably lower SEM (6° – 11°) and MDC (18° – 30°) ranges compared to comb and abduction tasks.

Bland-Altman plots, which depict the difference between two test sessions against the average of the two test sessions, were generated for the GH rotations in each of the five tasks. These plots can be found in Appendix I. Bland-Altman plots provide a visual check of the GH kinematics agreement between measurements obtained from two test sessions.

Table 4. *Test-retest reliability of the glenohumeral kinematics analyses*

	Task 1: Abduction			Task 2: Tie Apron			Task3: Comb through Hair			Task4: Flexion			Task5: Floor to Shoulder Lift		
Glenohumeral Abduction/Adduction	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.007	40	110	0.554	7	20	0.529	25	70	0.596	7	21	0.430	6	18
Maximum	-0.181	8	21	0.381	7	18	0.422	8	23	0.114	6	16	-0.084	4	11
Range of Motion	0.153	35	98	0.283	7	20	0.594	21	59	0.602	6	17	0.539	5	14
Glenohumeral Flexion Extension	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.447	6	16	0.688	5	14	0.746	4	12	0.472	5	15	0.392	6	18
Maximum	0.515	11	30	0.831	5	13	0.729	7	18	0.688	12	32	0.637	7	19
Range of Motion	0.599	11	32	0.799	5	13	0.800	8	21	0.827	9	25	0.509	7	20
Glenohumeral Internal/External Rotation	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs	ICC	SEM	MDCs
Minimum	0.640	11	31	0.599	8	22	0.511	15	43	0.639	8	22	0.764	7	19
Maximum	-0.076	34	93	0.607	9	24	0.386	19	54	0.710	6	18	0.630	6	18
Range of Motion	0.204	28	77	0.150	7	19	0.653	13	35	0.367	11	30	0.670	7	19

Heatmaps of ST and GH kinematics ICCs were generated to provide a visual representation of their reliability across different tasks (Figure 13 & Figure14). This visualization allows for easier interpretation of the range of ICC values, with darker shades of blue indicate lower reliability (poor to fair), while brighter shades of yellow represent higher reliability (good to excellent). The heatmap reveals that abduction tasks exhibited the lowest overall reliability across tasks for both ST (Figure 13) and GH (Figure 14) kinematic variables, with most discrete variables depicted in shades of blue or dark blue. Conversely, tasks such as floor to shoulder lift demonstrated predominantly light green to yellow colors, signifying overall good to excellent reliability, with approximately 62% of variables surpassing the good reliability threshold.

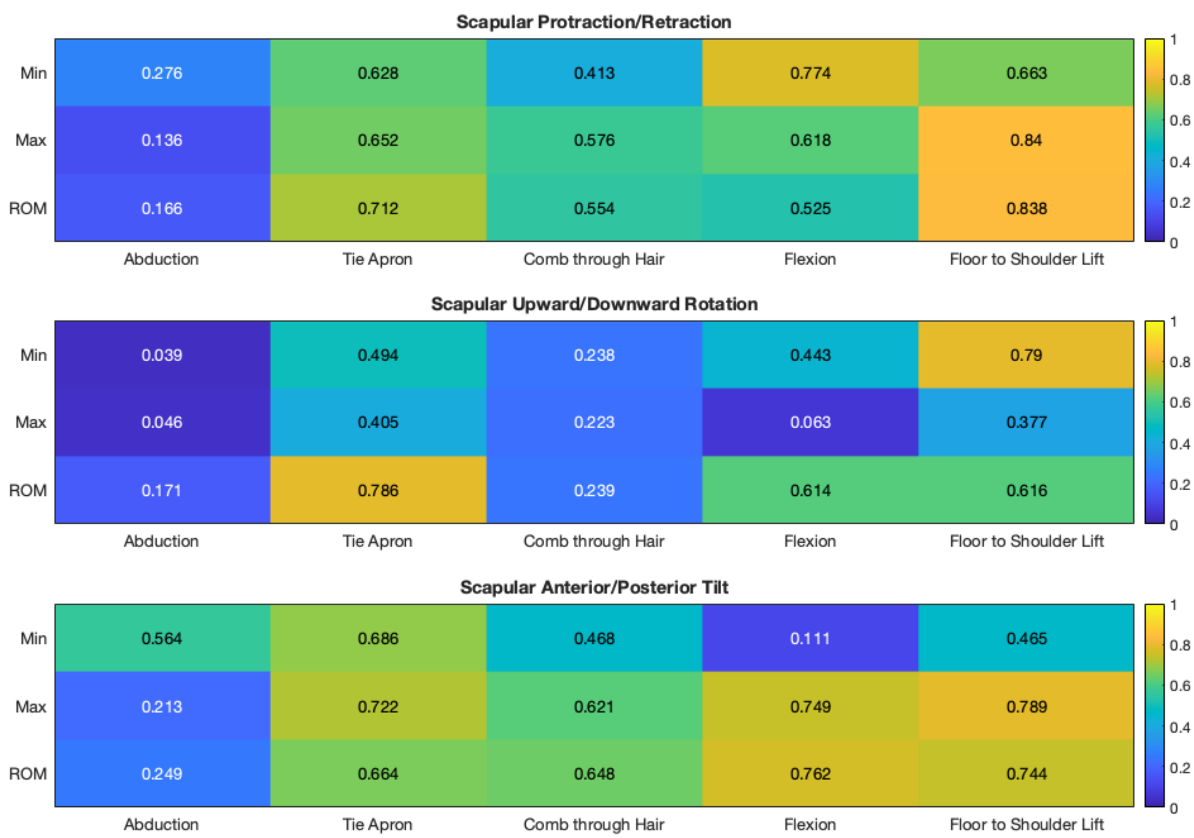


Figure 13. *Heatmap of ICC values for ST kinematics across five movement tasks*

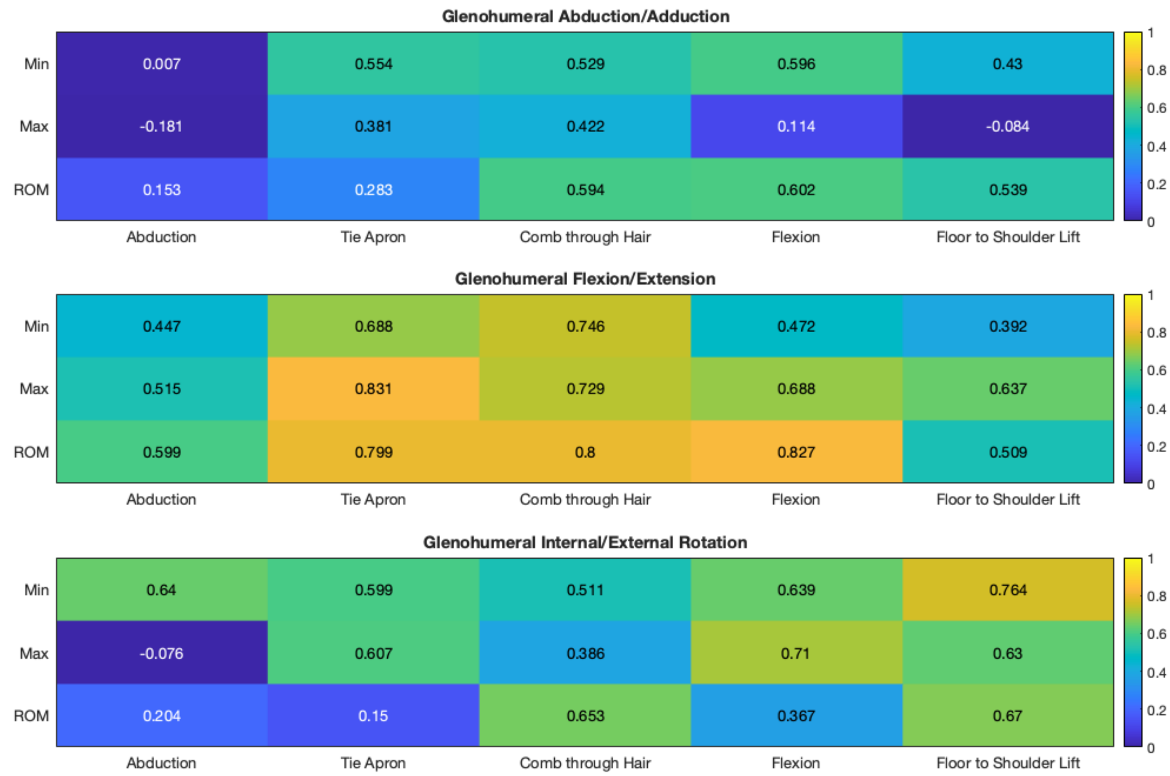


Figure 14. *Heatmap of ICC values for GH kinematics across five movement tasks*

5.3 Scapulothoracic Kinematics Patterns

Table 5 presents the group mean ROM (±1 SD) for each rotation of ST kinematics for two sessions. Upon examination, the abduction task exhibits a considerable difference in mean ROM for ST protraction/retraction and anterior/posterior tilt between the two test sessions. The SDs associated with these measurements are notably large, particularly during the second visit session. In contrast, for other tasks, the mean ROM differences between the two sessions are relatively small. However, it is worth noting that both the flexion and combing through hair tasks display significant SDs for some rotations in both test sessions (Table 5).

Table 5. *Mean ROM of ST kinematics for five tasks for two sessions (degrees)*

	Abduction		Tie Apron		Comb through Hair		Flexion		Floor to Shoulder Lift	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Protraction/Retraction	40 (±18)	66 (±45)	18 (±6)	18 (±6)	22 (±10)	20 (±9)	26 (±11)	34 (±17)	32 (±10)	31 (±7)
Upward/Downward Rotation	48 (±11)	46 (±15)	11 (±7)	11 (±6)	32 (±9)	28 (±11)	36 (±9)	35 (±16)	13 (±6)	14 (±7)
Anterior/Posterior Tilt	65 (±29)	91 (±51)	16 (±4)	16 (±4)	45 (±19)	43 (±16)	64 (±23)	70 (±33)	31 (±11)	30 (±7)

(S1 = test session 1; S2 = test session 2; mean ± 1 SD)

Figure 15 displays the group mean waveform data of ST kinematics for different rotations plotted against the completion percentage of tasks across five movement tasks between two test sessions. The waveform plot provided a more direct visualization of the substantial variability in mean values for ST protraction/retraction and tilts during the abduction task between the two sessions. Despite this variability, similarities are evident in the start and end degrees, as well as the overall movement pattern shape. Additionally, it was observed that, aside from the abduction task, the averaged waveform shapes remain similar between sessions, despite the presence of low reliability in some degrees of freedom in certain tasks, such as the comb through hair task.

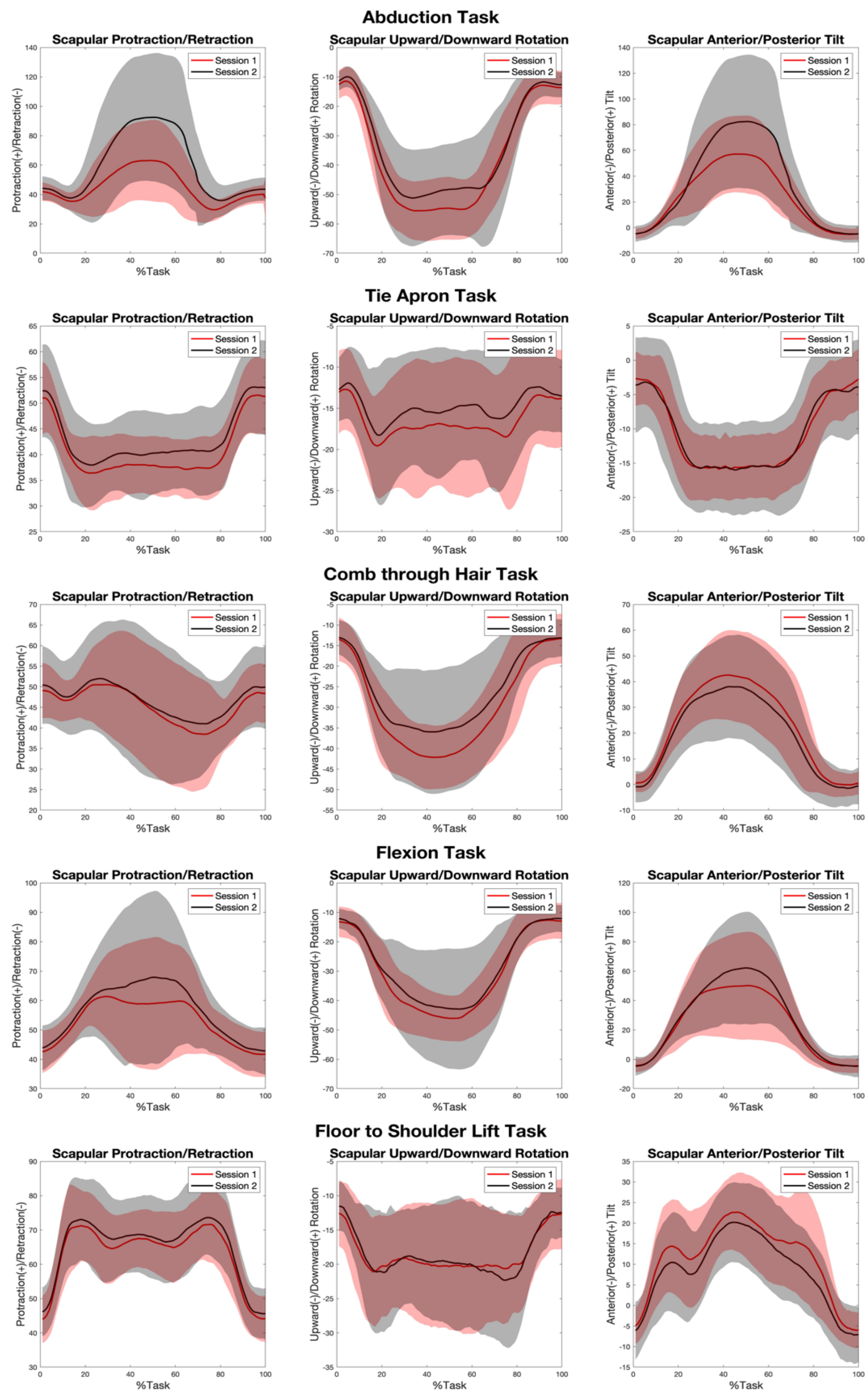


Figure 15. *Mean waveform data of ST kinematics across five movement tasks for both sessions. The bold lines represent the average (1=red; 2=black). Standard deviation is depicted via shading corresponding to each session by color.*

5.4 Glenohumeral Kinematics Patterns

Table 6 presents the group mean ROM (± 1SD) of GH kinematics for five tasks between two test sessions. The average ROM difference between the two test sessions for all joint rotations across tasks is within 7 degrees. However, similar to scapulothoracic kinematics, large standard deviations were observed in elevation-based tasks, indicating greater variability in measurements.

Table 6. *Mean ROM of GH kinematics for five tasks for two sessions (degrees)*

	Abduction		Tie Apron		Comb through Hair		Flexion		Floor to Shoulder Lift	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Abduction/Adduction	73 (±41)	71 (±37)	28 (±7)	33 (±9)	49 (±32)	56 (±36)	30 (±9)	29 (±10)	20 (±7)	23 (±8)
Flexion/Extension	52 (±15)	47 (±21)	58 (±11)	58 (±10)	45 (±16)	46 (±18)	77 (±20)	81 (±24)	53 (±10)	57 (±11)
Internal/External Rotation	52 (±36)	49 (±26)	26 (±6)	29 (±9)	41 (±24)	47 (±19)	43 (±11)	44 (±16)	32 (±11)	33 (±14)

(S1 = test session 1; S2 = test session 2; mean ± 1 SD)

Figure 16 illustrates the group mean GH kinematics averaged waveform for five movements between test sessions 1 (depicted in red) and 2 (depicted in black). Despite the presence of large variability within sessions and low reliability between sessions in some degrees of freedom across certain tasks, the mean averaged bold lines exhibit minimal differentiation (Figure 16). Furthermore, the overall shape of the waveform remains similar between sessions, suggesting consistency in movement patterns despite variability in individual measurements.

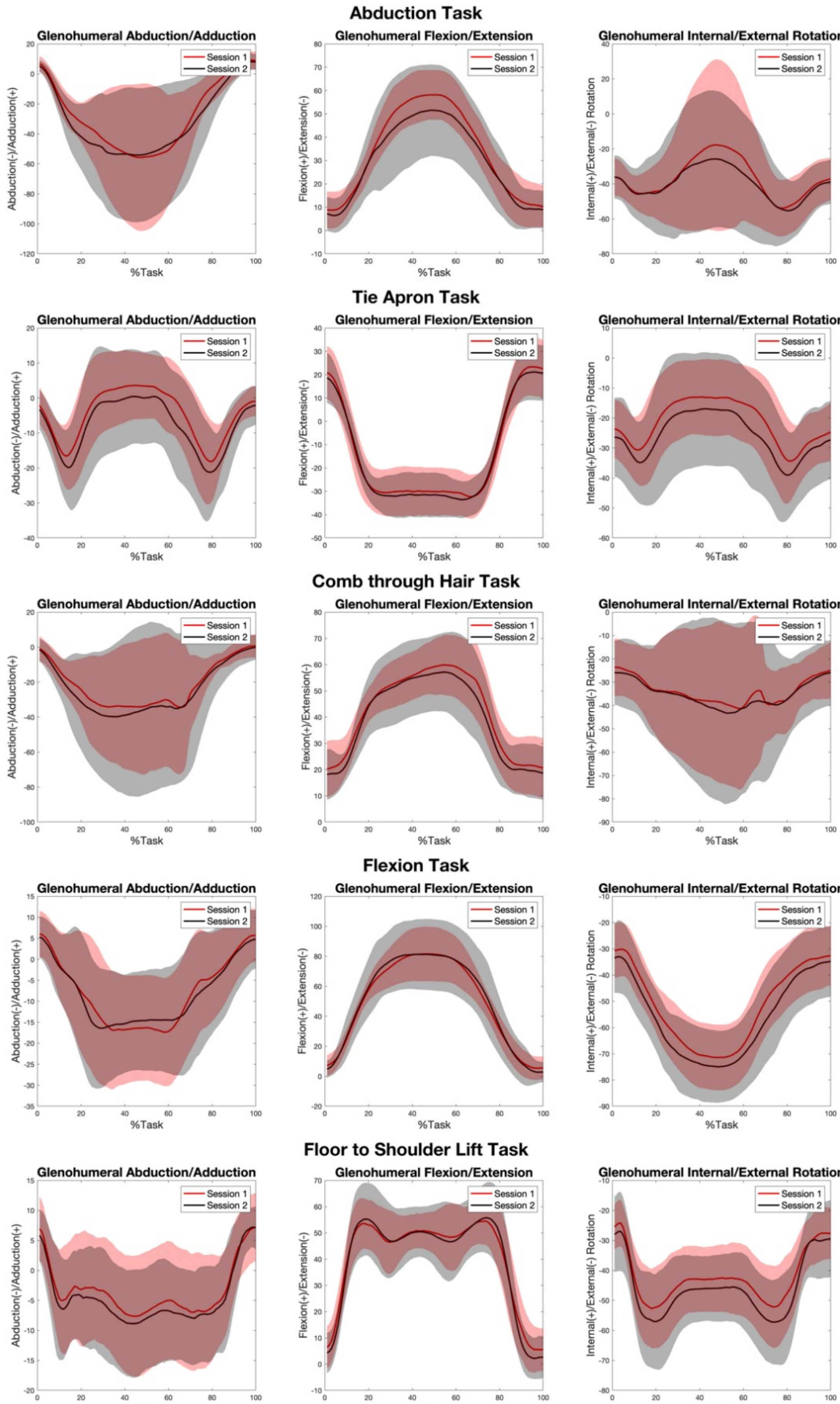


Figure 16. *Mean waveform data of GH kinematics across five movement tasks for both sessions. The bold lines represent the average (1=red; 2=black). Standard deviation is depicted via shading corresponding to each session by color.*

CHAPTER 6. DISCUSSION

The primary objective of this study was to assess the day-to-day reliability of the standardized shoulder biomechanical evaluation protocol, which encompasses single plane movements and ADLs, in a cohort of young, healthy participants. Based on findings from Friesen et al., (2023), it was hypothesized that tasks involving elevation of the shoulder would demonstrate greater reliability, ranging from good to excellent, compared to tasks that did not involve elevation, which were expected to show reliability ranging from fair to good. Evaluating the inter-day reliability of this protocol is crucial as it ensures the consistency and stability of the measurements over time. Such reliability is essential for longitudinal tracking methods aimed at reflecting changes to shoulder function, clinical progression and guiding rehabilitation efforts effectively. Additionally, this study contributed to the establishment of a baseline profile detailing the movement patterns of healthy individuals during the performance of specific upper extremity tasks. Baseline profiles can serve as a reference in clinical settings, enabling comparisons with individuals exhibiting clinical symptoms and aiding in the early detection and diagnosis of shoulder-related issues.

Contrary to the original hypothesis, the findings of the current study indicated that non-elevation-based tasks (Tie apron and Floor to Shoulder Lift) exhibited overall better ICC scores, with 61.1% of variables demonstrating good to excellent reliability in both ST and GH kinematics. In contrast, elevation-based tasks exhibited reliability above the good threshold in only 31.5% of ICCs.

6.1 Test-retest Reliability

For ST and GH kinematic variables' relative reliability, the results indicate that non-elevation-based tasks exhibited better overall reliability compared to elevation-based tasks. Among both ST and GH kinematics, the maximum abduction task exhibited the lowest reliability, as indicated by the overall lowest ICC values across variables. A key distinction in GH reliability compared to ST kinematics was observed: aside from abduction task, the GH kinematics in the remaining elevation-based tasks showed comparable reliability with the non-elevation-based tasks.

According to the format outlined by McGraw & Wong (1996) for calculating the two-way mixed effects absolute agreement ICC in SPSS, the value of an ICC is subject to the influence of various factors. Individual variability among participants, contributes to increased overall variability, potentially leading to lower reliability. Between-day variability, manifesting as fluctuations or alterations in measurements across days, can also diminish reliability by introducing inconsistency or instability in the data. External factors such as measurement error can also exacerbate variability. Understanding and addressing these factors are essential for the accurate interpretation and application of ICC values in both research and clinical contexts.

6.1.1 Between-subjects Variability

Larger between-subjects variability, as indicated by the measure of SD, were observed in the mean ROM for each kinematic variable in the elevation-based tasks compared to the non-elevation-based tasks (Table 5 and Table 6). Additionally, individual variability increased with increasing humeral elevation for both ST and GH rotations (Figure 15 and Figure 16). For ST kinematics during elevation tasks, the SD varied between 9° and 51°, contrasting with non-elevation tasks where the maximum SD for ST kinematics reaches only up to 11°. In GH kinematics during elevation tasks, the SD ranges from 9° to 41°, whereas a narrower range of SD, falling within 6° to 14°, is observed in non-elevation tasks. This substantial individual variability contributed to the lower reliability observed in the current elevation-based tasks.

The high individual variability of the ST and GH kinematics during elevation-based tasks presented can be attributed to several factors. Notable factors include participant instructions and physical set-up of the tasks. Participants in this study were encouraged to complete movements naturally, with relatively minimal movement restrictions and guidance. The start and end positions, as well as the specific movements, were explicitly standardized with clear verbal instructions provided prior to task initiation. For instance, in the hair combing task, participants were directed to initiate the movement with their hands on their lap, then proceed to move their hands toward the start of their hairline, simulating combing the hair until they reach the end of their hairline at the back of the head and returning to the starting position. However, strict adherence to specific movement planes was not enforced, and participants were not asked to restart or redo their trial if they deviated from the provided instructions. As another example, deviation from a single plane was particularly noticeable during planar flexion and abduction movements. This increased movement variability between and across participants. The nature of elevation-based tasks, with larger ROM, allows individuals the freedom to perform them with more variable strategies. This can increase variability compared to non-elevation tasks, particularly in the mid-range of the task. The tie apron task had limited ROM, while the lift tasks were constrained by the external object participants were instructed to reach for and lift. Both of these constraints restricted individual movement variability.

The postural and muscle redundancy inherent in the shoulder may further contribute to the significant between-subject variability observed in relatively less constrained elevation-based tasks. With its multitude of muscles, the shoulder offers high degrees of freedom and wide array of strategies in performing the same or similar movements (Bernstein, 1967; Kutch & Valero-Cuevas, 2011; Lugo et al., 2008). This redundancy provides the individuals with flexibility, adaptability, and robustness in movement control, allowing for alternative muscle activation and three-dimensional kinematic patterns to achieve the same desired movement outcome (Kutch & Valero-Cuevas, 2011). However, the theoretically infinite set of possibilities in muscle activation and coordination in the shoulder (Bernstein, 1967) makes replicating identical shoulder movement patterns among different individuals almost impossible. For example, reaching for an object on a high shelf can be accomplished by elevating the humerus to its maximum extent by one individual, while another individual may opt to elevate the scapula while keeping humeral elevation lower. This redundancy affects variability and reliability of shoulder kinematics between and within individuals for the same task instruction. Therefore, design of shoulder biomechanics protocols should account for the desired freedom of movement versus necessary movement constraints.

Constraining a shoulder movement or task can reduce the variability and postural and muscular redundancy between individuals. Previous studies strictly constrained movement within a single plane and provided visual checks and feedback (Haik et al., 2014; Ludewig & Cook, 2000; Roren et al., 2013; van den Noort et al., 2014; Yildiz et al., 2020). These studies utilized constrained and guided planar elevation movements with the aid of external targets, such as leader sticks, and predetermined arm movement speed using a metronome. As a result, they demonstrated lower individual variability, as indicated by significantly lower between-subjects SD values, in contrast to the findings of this study.

The ICC is influenced by variability between participants. According to Shoukri et al. (2008) and Streiner et al. (2024), the ICC is calculated as the ratio between-subjects variance and total variance. A positive relationship exists between inter-subject variability and measurement reliability. In essence, greater diversity among subjects makes it easier to distinguish between them, as long as the level of random error remains low or unchanged. This between-subjects variability may explain the contradictory trends observed in previous studies compared to the current one. In previous studies, where larger between-subjects variability was observed in high elevation tasks, most of these tasks demonstrated good to excellent reliability between days (Friesen et al., 2023; Haik et al., 2014; C. van Andel et al., 2009). In our study, despite observing large between-subjects variability in elevation tasks, these tasks exhibited lower reliability compared to non-elevation tasks. One speculation is that the effects of between-subjects variability on reliability may be compromised by significant between-days variability (measurement errors) in this study, as discussed in subsequent paragraphs. Since measurement errors contribute to the total variance, greater measurement errors lead to a decrease in the ICC, resulting in elevation tasks showing lower reliability than non-elevation tasks in our study. Further investigation into this phenomenon is warranted.

6.1.2 Between-days Variability

The between-days variability for ST and GH kinematics in the current protocol was indicated by the ICC and SEM, as presented in the Table 3 and Table 4. The SEM remains unaffected by between-subjects variability, as they are associated with the variance within each participant across repeated measurements (Andersen et al., 2014). The SEM serves as a valuable statistical tool in providing a measure of precision and reliability for individual scores on a measurement. One of its key applications is to establish a confidence interval around an observed score, within which the true score is likely to fall (Geerinck et al., 2019).

In contrast to the non-elevation-based tasks, which demonstrated low SEM values ranging from 2° to 5°, the elevation-based tasks exhibited notably higher day-to-day variability. This was evidenced by lower ICC values (indicating lower reliability) and high SEM values spanning from 3° to 40° for both ST and GH kinematic variables in elevation-based tasks.

The factors discussed previously that contribute to increased between-subjects variability can also influence the between-days variability in this study. For example, the encouragement of natural movement patterns and the absence of external restrictions in current protocol may increase postural redundancy and variability involved in elevation-based tasks. This is supported by Roren et al. (2013)'s study, where notably lower SEMs were reported during combing tasks conducted under more constrained movement instructions, focusing solely on below 90 degrees of elevation. Similarly, constraining planar elevation movements through the use of external targets with movement speed set by a metronome, may have further reduced the elevation task SEM in previous studies (van den Noort et al., 2014; Yildiz et al., 2020). The discrepancy in SEM values in the current and previous studies reinforces the significance of postural and muscular redundancy, and taking into account the specific instructions given for movements when interpreting reliability in shoulder tasks. Variations in the degree of elevation and the freedom permitted in movement execution can introduce differing levels of measurement errors between days.

The high SEMs and low ICCs observed in elevation tasks in this study may be further explained by the utilization of skin-based motion capture methods for tracking ST kinematics. The AMC method is a common, non-invasive method for measuring ST kinematics. It has been shown to be valid for measurements below 120 degrees of elevation, with measurement errors typically around or below 10° (Karduna et al., 2001; C. van Andel et al., 2009). During high elevation movements, bulging and contraction of the deltoid muscles can cause the AMC to lose contact with the acromion, leading to increased kinematic measurement errors (van Andel et al., 2009). AMC errors can escalate to as high as 25° when elevation exceeds 120 degrees (Karduna et al., 2001). The present study included maximal ROM elevation movements above 120 degrees. The inclusion of large ROM tasks beyond 120 degrees likely introduced scapular tracking errors that influenced measurement accuracy and reliability in elevation tasks compared to non-elevation tasks. However, In this study, all ST and GH kinematic variables during non-elevation-based tasks had SEM below 10°, indicating relatively consistent and good measurement precision between days. However, for the elevation-based tasks in this study, although larger SEMs exist compared to the non-elevation tasks, only the abduction task kinematics had SEMs greater than 25°. The SEMs of the other elevation-based tasks, such as comb and flexion tasks, fell within the errors caused by the AMC in high-elevation movements in this study. As there were different kinematic strategies utilized within and between participants, some of the larger SEM ranges in elevation-based tasks may be attributed to a kinematic-strategy-dependency of the AMC validity. For example, in response to factors such as fatigue or changes in task familiarity, a participant may utilize more elevation to complete the same task during their second session compared to their first session. Since the errors associated with AMC measurements are influenced by the elevation height, this adjustment in kinematic strategy leads to discrepancies in the outcomes between test sessions.

Low reliability was observed during abduction tasks within the current protocol, indicating potential additional sources of variability during this task. Lower reliability has consistently been reported in abduction compared to flexion, which is consistent with the observation in the current study. Tasks involving movements predominantly in the frontal plane, such as abduction, exhibited relatively low reliability across all variables in the present study. Lower reliability in abduction may be due to the more refined motor pattern development for elevating movements in front of the thorax, which are more frequently performed and practiced in daily activities (Friesen et al., 2023). Consequently, these refined movements may result in reduced day-to-day variability when participants perform the same task. Conversely, movements such as abduction, which involve less sophisticated motor control, may lead to higher variability between days.

The larger measurement errors and lower reliability observed in the abduction task in this study may also be attributed to specific kinematic strategies. For example, previous studies have highlighted ST protraction/retraction as particularly susceptible to skin movement artifacts errors (Friesen et al., 2023; Meskers et al., 2007; Thigpen et al., 2005; van Andel et al., 2009). In the current protocol, the abduction task involved greater ST protraction/retraction compared to other tasks, potentially exacerbating measurement errors and reducing reliability due to the significant skin movement artifacts.

6.1.3 Interpretation of Variability

The variability observed across different tasks in this study is closely linked to the remarkable postural and muscular redundancy and the high DOFs at the shoulder. This highlights the complexity in tracking and interpreting shoulder movements. Non-elevation tasks demonstrated high reliability, indicating their utility in detecting meaningful kinematic differences between measurements. In contrast, the low reliability observed in elevation-based tasks limits their effectiveness in detecting true differences. Further investigation is needed to improve their reliability and reduce errors. However, as discussed previously, various sources contribute to the high between-subjects variability and measurement errors in elevation tasks. Despite ongoing debate regarding their utilization, the elevation tasks in this study offer valuable insights into the shoulder redundancy present in shoulder movements across young, healthy individuals and between testing sessions. This variability can serve as a foundational reference point for understanding how healthy and young individuals' shoulder kinematics can vary due to postural redundancy at the shoulder. Future studies can use this variability as a basis for evaluating and comparing different movement patterns. Understanding variability caused by shoulder redundancy compared to other causes of variability can inform sources of bias, study design considerations, methodological improvements and interpretation of results. In clinical applications, the baseline variability in young and healthy populations can help determine whether observed differences after intervention/rehabilitation are due to true changes or typical shoulder variability stemming from redundancy nature.

6.2 Kinematic Profiles

The presented kinematic profiles provide valuable insights into the movement patterns and ROM exhibited by young and healthy populations during specific movement tasks (Figure 15 and 16). Individuals with shoulder pain and pathologies frequently adopt compensatory strategies during movement, leading to observed kinematic alterations. In this context, typical normative kinematic profiles serve as a foundational reference for clinicians and researchers, aiding in the identification of abnormalities and monitoring of rehabilitation progress. The utility of such profiles can be illustrated through Ludewig & Cook (2000), who observed that individuals with shoulder impingement would display increased anterior tilt of the scapula as elevation angle increased. However, the present study involving healthy young individuals contradicts this trend, showing increased posterior tilt with increasing elevation (Figure 15). This highlights the importance of normative data in understanding and interpreting shoulder kinematics, particularly in distinguishing between healthy and pathological profiles.

In addition to the kinematic movement patterns established, the MDCs for ST and GH kinematics (Table 3 and Table 4) also contribute to the interpretation and application of biomechanical data. For the elevation-based tasks in the current study, the MDCs ranged from 12 to 110 degrees across both ST and GH kinematic variables (Table 3 and Table 4). This indicates that in order to detect significant changes in kinematic variables between two test sessions during elevation tasks, the differences observed after intervention can be up to 110 degrees. In contrast, the MDC in peak values and ROM between sessions observed in the non-elevation tasks of this study were overall much smaller than those observed in elevation tasks, with all values below 24 degrees.

While MDCs for elevation tasks were spread across a large range, MDCs of non-elevation tasks were similar to previous studies of shoulder biomechanics. Previous research reported MDC cut-off values of 20 degrees for ST and GH kinematic rotations and task types to detect true changes before and after interventions (Friesen et al., 2023; Haik et al., 2014; van den Noort et al., 2014). This implies that changes in kinematic discrete variables exceeding 20 degrees may be considered significant and not merely due to variability or measurement errors. In the present study, similar MDCs of 24 degrees for non-elevation tasks were identified as meaningful alterations in discrete joint angles between sessions. However, significant differences between individuals with shoulder injuries and healthy control groups are consistently below 15 degrees (Haik et al., 2014; Ludewig & Cook, 2000; McClure et al., 2006; Miura et al., 2017; Schnorenberg et al., 2022). The MDCs of 24 degrees during non-elevation tasks found in this study exceed this range. Applying this value in clinical practice may lead to misinterpretation of treatment effects. Therefore, caution should be taken when using the MDCs derived from this study. If necessary, MDC values should be reassessed in the specific population of interest to ensure their validity and applicability in clinical settings.

The MDCs for the elevation-based tasks were found to be significantly greater than the cut-off MDCs suggested in previous studies, raising questions about their applicability in clinical practice. Given the substantial individual and between-days variability observed in elevation tasks, it may be more reasonable to establish higher MDC values for these specific tasks. However, in the current study, the low reliability of elevation tasks and large variability suggest that the MDCs could potentially be comparable to or even greater than the mean ROM values presented in Table 5 and Table 6. For example, the MDC for ST anterior/posterior tilt ROM during abduction tasks was

103 degrees (Table 3). However, the averaged ROM for this specific task and rotation was 65 degrees during the first visit and 91 degrees during the second visit (Table 5). Given that such substantial changes in ROM (MDC comparable to or greater than the average ROM) are unlikely in realistic clinical scenarios, the utilization of MDCs for elevation tasks warrants further investigation to ensure their accuracy and relevance in clinical decision-making.

6.3 Limitations

Several limitations were identified in this study. The primary limitation pertains to the study sample. First, this study had a relatively small sample size, which may have implications for the reliability outcomes observed in this study. The homogeneity of the small sample population in terms of demographic characteristics could also be considered a limitation. According to the ICC formula, higher ICC values are more likely to be produced by heterogeneous subjects than by homogeneous ones, as relative reliability is influenced by the ratio of variability between subjects and total variability (Muir et al., 2010). The research was carried out among a cohort of young, healthy individuals aged between 18 and 30 years, and consequently, the findings are specifically relevant to this demographic. However, before extrapolating the current protocol to broader populations, it is imperative to conduct reliability assessments across various age groups and clinical populations.

Another significant limitation of this study pertains to the surface-based measurement approach employed. Surface sensors utilized for collecting ST kinematics are susceptible to errors, stemming from difficulties in palpating bony landmarks and skin motion with respect to the underlying bone during data collection, as noted in previous research (Haik et al., 2014). Similarly, the skin-mounted ST measurement technique, AMC, is prone to errors at higher humeral elevations (Karduna et al., 2001). The accuracy of the AMC diminishes above 120 degrees of elevation (Karduna et al., 2001), potentially impacting the between-day reliability and exacerbating measurement errors during the tasks involving maximum flexion, abduction and comb through hair.

This study also recommends future improvements in the calibration process. While a single calibration in the anatomical position was utilized in this study, previous research suggests that employing double or multiple calibrations in various positions can enhance accuracy (Brochard et al., 2011; Friesen et al., 2023). It was found that multiple calibrations reduce skin artifact errors and provide scapular orientation and motion measurements comparable to those obtained by palpation along any axis, particularly at high degrees of humeral elevation (Brochard et al., 2011; Meskers et al., 2007; Richardson et al., 2016). Incorporating such calibration methods may lead to increased reliability and reduced errors, especially in elevation-based tasks.

6.4 Future Directions

Given the relatively small sample size recruited in the present study, future studies should consider expanding the sample size. A larger sample size may enhance the statistical power of the analysis, thereby allowing for a more comprehensive evaluation of the reliability of the current protocol.

Despite the low between-days reliability observed in elevation-based tasks in this study, they remain crucial in both research and clinical settings for assessing shoulder function. Therefore, further investigation is needed to refine and include elevation-based tasks in a standardized protocol. Given that the aim of this study was to replicate ADLs, movements were executed in a relatively unconstrained manner. To improve the reliability of elevation tasks in future studies, it may be beneficial to incorporate visual feedback, utilize external targets to guide movements, or regulate movement speed to constrain the large degrees of freedom at the shoulder.

Additionally, as only discrete measurements were assessed for reliability in this study, future investigations could employ continuous movement analysis techniques such as coefficient of multiple correlation (CMC) or statistical parametric mapping (SPM) to compare the reliability of movement waveforms, potentially providing richer insights into the current protocol's reliability.

6.5 Project Significance

Biomechanical research plays a crucial role in comprehending the complex nature of shoulder function and injury. However, the presence of conflicting approaches and findings within the biomechanical field hinders progress. There are inconsistencies across studies in the quantification of shoulder kinematics during ADLs and standardization in movement task selection. The findings of the current study may contribute to the eventual establishment of a reliable, and comprehensive shoulder biomechanical evaluation protocol standard tailored for ADLs.

Standardization fosters enhanced comparability of studies outcomes and facilitates increased understanding of shoulder biomechanics over time. Through the establishment of a standardized protocol that includes consistent utilization of predefined movement tasks representative of ADLs and adherence to standardized guidelines, researchers can attain more dependable and reproducible measurements of shoulder kinematics. Given the overall reliability observed in both ST and GH kinematics, the current non-elevation-based tasks hold promise for assessing shoulder function during functional tasks in both research and clinical settings, albeit with caution. Moreover, the ST and GH kinematics profiles elucidated in this study hold promise for integration into comprehensive kinematic profiles. Such profiles could serve as valuable tools for detecting kinematic differences between uninjured individuals and those with pathological shoulder motion.

CHAPTER 7. CONCLUSION

The aim of this study was to assess the between-day reliability of the biomechanical evaluation of shoulder function in young, healthy adults without a history of shoulder injury. Additionally, the study aimed to quantify the GH and ST kinematics associated with shoulder functional tasks in this population.

ST and GH kinematics during non-elevation-based tasks (tie apron and floor to shoulder lift tasks) showed overall good reliability between days. However, elevation-based tasks (including maximum abduction, flexion, and comb through hair tasks) exhibited relatively low ICC values and high SEMs. Further analysis is warranted, and the implementation of external targets or stricter guidelines may enhance the reliability of these tasks. This may enable elevation-based tasks to be integrated into standardized protocols for assessing shoulder function more reliably.

This study also contributed to the establishment of normative shoulder kinematics in a healthy, young populations in the current protocol. This normative profile and variability baseline play a crucial role in facilitating the detection of kinematic abnormalities and pathologies, providing clinicians and researchers with valuable reference points for identifying deviations from typical movement patterns and monitoring changes over time.

References

Abboud, J. A., & Soslowsky, L. J. (2002). Interplay of the Static and Dynamic Restraints in Glenohumeral Instability. *Clinical Orthopaedics and Related Research®*, *400*, 48. https://journals.lww.com/clinorthop/fulltext/2002/07000/interplay_of_the_static_and_dynamic_restraints_in.7.aspx

Alt Murphy, M., Murphy, S., Persson, H. C., Bergström, U.-B., & Sunnerhagen, K. S. (2018). Kinematic Analysis Using 3D Motion Capture of Drinking Task in People With and Without Upper-extremity Impairments. *Journal of Visualized Experiments : JoVE*, *133*, 57228. https://doi.org/10.3791/57228

Andersen, K. S., Christensen, B. H., Samani, A., & Madeleine, P. (2014). Between-day reliability of a hand-held dynamometer and surface electromyography recordings during isometric submaximal contractions in different shoulder positions. *Journal of Electromyography and Kinesiology*, *24*(5), 579–587. https://doi.org/10.1016/j.jelekin.2014.05.007

Beninato, M., & Portney, L. G. (2011). Applying concepts of responsiveness to patient management in neurologic physical therapy. *Journal of Neurologic Physical Therapy: JNPT*, *35*(2), 75–81. https://doi.org/10.1097/NPT.0b013e318219308c

Bernardina, G. R. D., Monnet, T., Pinto, H. T., Barros, R. M. L. de, Cerveri, P., & Silvatti, A. P. (n.d.). Are Action Sport Cameras Accurate Enough for 3D Motion Analysis? A Comparison With a Commercial Motion Capture System. *Journal of Applied Biomechanics*, *35*(1), 80–86. https://doi.org/10.1123/jab.2017-0101

Bernstein, N. A. (1967). The coordination and regulation of movements. Pergamon Press, Oxford.

Bet-Or, Y., van den Hoorn, W., Johnston, V., & O'Leary, S. (2017). Reliability and Validity of an Acromion Marker Cluster for Recording Scapula Posture at End Range Clavicle Protraction, Retraction, Elevation, and Depression. *Journal of Applied Biomechanics*, *33*(5), 379–383. https://doi.org/10.1123/jab.2017-0058

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Boser, Q. A., Valevicius, A. M., Lavoie, E. B., Chapman, C. S., Pilarski, P. M., Hebert, J. S., & Vette, A. H. (2018). Cluster-based upper body marker models for three-dimensional kinematic analysis: Comparison with an anatomical model and reliability analysis. *Journal of Biomechanics*, *72*, 228–234. https://doi.org/10.1016/j.jbiomech.2018.02.028

Briel, S., Olivier, B., & Mudzi, W. (2022). Scapular force: Couple ratios in healthy shoulders – An observational study reflecting typical values. *The South African Journal of Physiotherapy*, *78*(1), 1619. https://doi.org/10.4102/sajp.v78i1.1619

Brochard, S., Lempereur, M., & Rémy-Néris, O. (2011). Accuracy and reliability of three methods of recording scapular motion using reflective skin markers. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine*, *225*(1), 100–105. https://doi.org/10.1243/09544119JEIM830

Bruttel, H., Spranz, D. M., Bülhoff, M., Aljohani, N., Wolf, S. I., & Maier, M. W. (2019). Comparison of glenohumeral and humerothoracical range of motion in healthy controls, osteoarthritic patients and patients after total shoulder arthroplasty performing different activities of daily living. *Gait & Posture*, *71*, 20–25. https://doi.org/10.1016/j.gaitpost.2019.04.001

Burkhart, S. S. (1991). Arthroscopic Treatment of Massive Rotator Cuff Tears: Clinical Results and Biomechanical Rationale. *Clinical Orthopaedics and Related Research*, *267*(NA;), 45???56. https://doi.org/10.1097/00003086-199106000-00006

Chang, L.-R., Anand, P., & Varacallo, M. (2023). Anatomy, Shoulder and Upper Limb, Glenohumeral Joint. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK537018/

Cools, A. M., Declercq, G. A., Cambier, D. C., Mahieu, N. N., & Witvrouw, E. E. (2007). Trapezius activity and intramuscular balance during isokinetic exercise in overhead athletes with impingement symptoms. *Scandinavian Journal of Medicine and Science in Sports*, *17*(1), 25–33. Scopus. https://doi.org/10.1111/j.1600-0838.2006.00570.x

De Baets, L., Van Deun, S., Monari, D., & Jaspers, E. (2016). Three-dimensional kinematics of the scapula and trunk, and associated scapular muscle timing in individuals with stroke. *Human Movement Science*, *48*, 82–90. https://doi.org/10.1016/j.humov.2016.04.009

de Groot, J. H. (1997). The variability of shoulder motions recorded by means of palpation. *Clinical Biomechanics*, *12*(7–8), 461–472. https://doi.org/10.1016/S0268-0033(97)00031-4

de Groot, J. H., & Brand, R. (2001). A three-dimensional regression model of the shoulder rhythm. *Clinical Biomechanics*, *16*(9), 735–743. https://doi.org/10.1016/S0268-0033(01)00065-1

Doorenbosch, C. A. M., Harlaar, J., & Veeger, D. (H. E. J.). (2003). The globe system: An unambiguous description of shoulder positions in daily life movements. *The Journal of Rehabilitation Research and Development*, *40*(2), 149. https://doi.org/10.1682/JRRD.2003.03.0149

Edemekong, P. F., Bomgaars, D. L., Sukumaran, S., & Schoo, C. (2022). Activities of Daily Living. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK470404/

Elzanie, A., & Varacallo, M. (2022). Anatomy, Shoulder and Upper Limb, Deltoid Muscle. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK537056/

Engdahl, S. M., & Gates, D. H. (2018). Reliability of upper limb and trunk joint angles in healthy adults during activities of daily living. *Gait & Posture*, *60*, 41–47. https://doi.org/10.1016/j.gaitpost.2017.11.001

Frank, R. M., Ramirez, J., Chalmers, P. N., McCormick, F. M., & Romeo, A. A. (2013). Scapulothoracic Anatomy and Snapping Scapula Syndrome. *Anatomy Research International*, *2013*, 1–9. https://doi.org/10.1155/2013/635628

Franovic, S., Zhou, Y., Lau, E., Pietroski, A. D., Kuhlmann, N. A., Singh, V., Chen, C., & Muh, S. J. (2020). A Pilot Study for Assessing a Novel Method of Measuring Shoulder Activation in Healthy Volunteers Using Surface Electromyography. *Archives of Orthopaedics*, *Volume 1*(Issue 4), Article Issue 4. https://doi.org/10.33696/Orthopaedics.1.019

Friesen, K. B., & Lang, A. E. (2022). Do Musculoskeletal Disorders Affect Work Tasks in Farmers: A Study of Rural Saskatchewan. *Journal of Occupational and Environmental Medicine*, *64*(9), e591. https://doi.org/10.1097/JOM.0000000000002637

Friesen, K. B., Wu, L. Z., Waslen, A., & Lang, A. E. (2023). Defining repeatability for scapulothoracic and thoracohumeral motion during the novel work-related activities and functional task (WRAFT) protocol. *Journal of Biomechanics*, *153*, 111596. https://doi.org/10.1016/j.jbiomech.2023.111596

Furlan, L., & Sterr, A. (2018). The Applicability of Standard Error of Measurement and Minimal Detectable Change to Motor Learning Research—A Behavioral Study. *Frontiers in Human Neuroscience*, *12*, 95. https://doi.org/10.3389/fnhum.2018.00095

Gates, D. H., Walters, L. S., Cowley, J., Wilken, J. M., & Resnik, L. (2016). Range of Motion Requirements for Upper-Limb Activities of Daily Living. *The American Journal of Occupational Therapy*, *70*(1), 7001350010p1-7001350010p10. https://doi.org/10.5014/ajot.2016.015487

Geerinck, A., Alekna, V., Beaudart, C., Bautmans, I., Cooper, C., De Souza Orlandi, F., Konstantynowicz, J., Montero-Errasquín, B., Topinková, E., Tsekoura, M., Reginster, J.-Y., & Bruyère, O. (2019). Standard error of measurement and smallest detectable change of the Sarcopenia Quality of Life (SarQoL) questionnaire: An analysis of subjects from 9 validation studies. *PLoS ONE*, *14*(4), e0216065. https://doi.org/10.1371/journal.pone.0216065

Gill, T. K., Shanahan, E. M., Tucker, G. R., Buchbinder, R., & Hill, C. L. (2020). Shoulder range of movement in the general population: Age and gender stratified normative data using a community-based cohort. *BMC Musculoskeletal Disorders*, *21*(1), 676. https://doi.org/10.1186/s12891-020-03665-9

Haik, M. N., Alburquerque-Sendín, F., & Camargo, P. R. (2014). Reliability and Minimal Detectable Change of 3-Dimensional Scapular Orientation in Individuals With and Without Shoulder Impingement. *Journal of Orthopaedic & Sports Physical Therapy*, *44*(5), 341–349. https://doi.org/10.2519/jospt.2014.4705

Halder, A. M., Itoi, E., & An, K.-N. (2000). ANATOMY AND BIOMECHANICS OF THE SHOULDER. *Orthopedic Clinics of North America*, *31*(2), 159–176. https://doi.org/10.1016/S0030-5898(05)70138-3

Hansen, G. M., Kersting, U. G., Pedersen, A. R., Svendsen, S. W., & Nielsen, J. F. (2019). Three-dimensional kinematics of shoulder function in stroke patients: Inter- and intra-rater reliability. *Journal of Electromyography and Kinesiology*, *47*, 35–42. https://doi.org/10.1016/j.jelekin.2019.05.006

Hellem, A., Shirley, M., Schilaty, N., & Dahm, D. (2019). Review of Shoulder Range of Motion in the Throwing Athlete: Distinguishing Normal Adaptations from Pathologic Deficits. *Current Reviews in Musculoskeletal Medicine*, *12*(3), 346–355. https://doi.org/10.1007/s12178-019-09563-5

Hill, C. L., Gill, T. K., Shanahan, E. M., & Taylor, A. W. (2010). Prevalence and correlates of shoulder pain and stiffness in a population-based study: The North West Adelaide Health Study: Prevalence and correlates of shoulder pain and stiffness in a population-based study. *International Journal of Rheumatic Diseases*, *13*(3), 215–222. https://doi.org/10.1111/j.1756-185X.2010.01475.x

Hodgetts, C. J., Leboeuf-Yde, C., Beynon, A., & Walker, B. F. (2021). Shoulder pain prevalence by age and within occupational groups: A systematic review. *Archives of Physiotherapy*, *11*(1), 24. https://doi.org/10.1186/s40945-021-00119-w

Hodgetts, C., & Walker, B. (2021). Epidemiology, common diagnoses, treatments and prognosis of shoulder pain: A narrative review. *International Journal of Osteopathic Medicine*, *42*, 11–19. https://doi.org/10.1016/j.ijosm.2021.10.006

Högfors, C., Peterson, B., Sigholm, G., & Herberts, P. (1991a). Biomechanical model of the human shoulder joint—II. The shoulder rhythm. *Journal of Biomechanics*, *24*(8), 699–709. https://doi.org/10.1016/0021-9290(91)90334-J

Imhoff, A. B., & Savoie, F. H. (Eds.). (2019). *Rotator cuff across the life span: ISAKOS consensus book*. Springer.

Inman, V. T., deC. M. Saunders, J. B., & Abbott, L. C. (1944). OBSERVATIONS ON THE FUNCTION OF THE SHOULDER JOINT. *JBJS*, *26*(1), 1. https://journals.lww.com/jbjsjournal/Citation/1944/26010/OBSERVATIONS_ON_THE_FUNCTION_OF_THE_SHOULDER_JOINT.1.aspx

International Classification of Functioning, Disability and Health (ICF). (n.d.). Retrieved January 2, 2023, from https://www.who.int/standards/classifications/international-classification-of-functioning-disability-and-health

Jaspers, E., Feys, H., Bruyninckx, H., Harlaar, J., Molenaers, G., & Desloovere, K. (2011). Upper limb kinematics: Development and reliability of a clinical protocol for children. *Gait & Posture*, *33*(2), 279–285. https://doi.org/10.1016/j.gaitpost.2010.11.021

Johnson, G. R., Stuart, P. R., & Mitchell, S. (1993). A method for the measurement of three-dimensional scapular movement. *Clinical Biomechanics*, *8*(5), 269–273. https://doi.org/10.1016/0268-0033(93)90037-I

Karduna, A. R., McClure, P. W., Michener, L. A., & Sennett, B. (2001). Dynamic Measurements of Three-Dimensional Scapular Kinematics: A Validation Study. *Journal of Biomechanical Engineering*, *123*(2), 184–190. https://doi.org/10.1115/1.1351892

Kelly, B. T., Williams, R. J., Cordasco, F. A., Backus, S. I., Otis, J. C., Weiland, D. E., Altchek, D. W., Craig, E. V., Wickiewicz, T. L., & Warren, R. F. (2005). Differential patterns of muscle activation in patients with symptomatic and asymptomatic rotator cuff tears. *Journal of Shoulder and Elbow Surgery*, *14*(2), 165–171. https://doi.org/10.1016/j.jse.2004.06.010

Kent, B. E. (1971). Functional Anatomy of the Shoulder Complex: A Review. *Physical Therapy*, *51*(8), 867–888. https://doi.org/10.1093/ptj/51.8.867

Kolk, A., Henseler, J. F., de Witte, P. B., van Zwet, E. W., van der Zwaal, P., Visser, C. P. J., Nagels, J., Nelissen, R. G. H. H., & de Groot, J. H. (2017). The effect of a rotator cuff tear and its size on three-dimensional shoulder motion. *Clinical Biomechanics*, *45*, 43–51. https://doi.org/10.1016/j.clinbiomech.2017.03.014

Kontaxis, A., Cutti, A. G., Johnson, G. R., & Veeger, H. E. J. (2009). A framework for the definition of standardized protocols for measuring upper-extremity kinematics. *Clinical Biomechanics*, *24*(3), 246–253. https://doi.org/10.1016/j.clinbiomech.2008.12.009

Kutch, J. J., & Valero-Cuevas, F. J. (2011). Muscle redundancy does not imply robustness to muscle dysfunction. *Journal of Biomechanics*, *44*(7), 1264–1270. https://doi.org/10.1016/j.jbiomech.2011.02.014

Lang, A. E., Dickerson, C. R., Kim, S. Y., Stobart, J., & Milosavljevic, S. (2019). Impingement pain affects kinematics of breast cancer survivors in work-related functional tasks. *Clinical Biomechanics*, *70*, 223–230. https://doi.org/10.1016/j.clinbiomech.2019.10.001

Lawrence, R. L., Braman, J. P., Staker, J. L., Laprade, R. F., & Ludewig, P. M. (2014). Comparison of 3-Dimensional Shoulder Complex Kinematics in Individuals With and Without Shoulder Pain, Part 2: Glenohumeral Joint. *Journal of Orthopaedic & Sports Physical Therapy*, *44*(9), 646-B3. https://doi.org/10.2519/jospt.2014.5556

Lee, K.-S., Park, J.-H., Beom, J., & Park, H.-S. (2018). Design and Evaluation of Passive Shoulder Joint Tracking Module for Upper-Limb Rehabilitation Robots. *Frontiers in Neurorobotics*, *12*, 38. https://doi.org/10.3389/fnbot.2018.00038

Lempereur, M., Brochard, S., Mao, L., & Rémy-Néris, O. (2012). Validity and reliability of shoulder kinematics in typically developing children and children with hemiplegic cerebral palsy. *Journal of Biomechanics*, *45*(11), 2028–2034. https://doi.org/10.1016/j.jbiomech.2012.05.020

Lin, J., Hsieh, S.-C., Cheng, W.-C., Chen, W. C., & Lai, Y. (2011). Adaptive patterns of movement during arm elevation test in patients with shoulder impingement syndrome. *Journal of Orthopaedic Research*, *29*(5), 653–657. https://doi.org/10.1002/jor.21300

Liu, W., Waller, S. M., Kepple, T., & Whitall, J. (2013). Compensatory arm reaching strategies after stroke: Induced position analysis. *Journal of Rehabilitation Research and Development*, *50*(1), 71–84. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3711110/

Longo, U. G., De Salvatore, S., Carnevale, A., Tecce, S. M., Bandini, B., Lalli, A., Schena, E., & Denaro, V. (2022). Optical Motion Capture Systems for 3D Kinematic Analysis in Patients with Shoulder Disorders. *International Journal of Environmental Research and Public Health*, *19*(19), 12033. https://doi.org/10.3390/ijerph191912033

Ludewig, P. M., & Cook, T. M. (2000). Alterations in Shoulder Kinematics and Associated Muscle Activity in People With Symptoms of Shoulder Impingement. *Physical Therapy*, *80*(3), 276–291. https://doi.org/10.1093/ptj/80.3.276

Ludewig, P. M., Phadke, V., Braman, J. P., Hassett, D. R., Cieminski, C. J., & LaPrade, R. F. (2009). Motion of the Shoulder Complex During Multiplanar Humeral Elevation: *The Journal of Bone and Joint Surgery-American Volume*, *91*(2), 378–389. https://doi.org/10.2106/JBJS.G.01483

Lugo, R., Kung, P., & Ma, C. B. (2008). Shoulder biomechanics. *European Journal of Radiology*, *68*(1), 16–24. https://doi.org/10.1016/j.ejrad.2008.02.051

Luime, J., Koes, B., Hendriksen, I., Burdorf, A., Verhagen, A., Miedema, H., & Verhaar, J. (2004). Prevalence and incidence of shoulder pain in the general population; a systematic review. *Scandinavian Journal of Rheumatology*, *33*(2), 73–81. https://doi.org/10.1080/03009740310004667

Maciukiewicz, J. M., Hussein, A. T. S., Mourtzakis, M., & Dickerson, C. R. (2022). An evaluation of upper limb strength and range of motion of breast cancer survivors immediately following treatment. *Clinical Biomechanics*, *96*, 105666. https://doi.org/10.1016/j.clinbiomech.2022.105666

MacLean, K. F. E., Chopp, J. N., Grewal, T.-J., Picco, B. R., & Dickerson, C. R. (2014). Three-dimensional comparison of static and dynamic scapular motion tracking techniques. *Journal of Electromyography and Kinesiology*, *24*(1), 65–71. https://doi.org/10.1016/j.jelekin.2013.09.011

Magermans, D. J., Chadwick, E. K. J., Veeger, H. E. J., & van der Helm, F. C. T. (2005). Requirements for upper extremity motions during activities of daily living. *Clinical Biomechanics*, *20*(6), 591–599. https://doi.org/10.1016/j.clinbiomech.2005.02.006

Matsen, F. A. (Ed.). (1994). *Practical evaluation and management of the shoulder*. Saunders.

McClure, P. W., Michener, L. A., & Karduna, A. R. (2006). Shoulder Function and 3-Dimensional Scapular Kinematics in People With and Without Shoulder Impingement Syndrome. *Physical Therapy*, *86*(8), 1075–1090. https://doi.org/10.1093/ptj/86.8.1075

McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients: Psychological Methods. *Psychological Methods*, *1*(1), 30–46. https://doi.org/10.1037/1082-989X.1.1.30

Mell, A. G., LaScalza, S., Guffey, P., Ray, J., Maciejewski, M., Carpenter, J. E., & Hughes, R. E. (2005). Effect of rotator cuff pathology on shoulder rhythm. *Journal of Shoulder and Elbow Surgery*, *14*(1), S58–S64. https://doi.org/10.1016/j.jse.2004.09.018

Meskers, C. G. M., van de Sande, M. A. J., & de Groot, J. H. (2007). Comparison between tripod and skin-fixed recording of scapular motion. *Journal of Biomechanics*, *40*(4), 941–946. https://doi.org/10.1016/j.jbiomech.2006.02.011

Mesquita, I. A., Fonseca, P. F. P. da, Borgonovo-Santos, M., Ribeiro, E., Pinheiro, A. R. V., Correia, M. V., & Silva, C. (2020). Comparison of upper limb kinematics in two activities of daily living with different handling requirements. *Human Movement Science*, *72*, 102632. https://doi.org/10.1016/j.humov.2020.102632

Metan, S. S., Krishna, P., & Mohankumar, G. C. (2014). FEM Model an Effective Tool to Evaluate Von Mises Stresses in Shoulder Joint and Muscles for Adduction and Abduction. *Procedia Materials Science*, *5*, 2090–2098. https://doi.org/10.1016/j.mspro.2014.07.544

Michener, L. A., Elmore, K. A., Darter, B. J., & Timmons, M. K. (2016). Biomechanical measures in participants with shoulder pain: Intra-rater reliability. *Manual Therapy*, *22*, 86–93. https://doi.org/10.1016/j.math.2015.10.011

Michener, L. A., McClure, P. W., & Sennett, B. J. (2002). American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form, patient self-report section: Reliability, validity, and responsiveness. *Journal of Shoulder and Elbow Surgery*, *11*(6), 587–594. https://doi.org/10.1067/mse.2002.127096

Miura, Y., Kai, Y., Morihara, T., Fukushima, H., Furukawa, R., Sukenari, T., Kida, N., & Nomura, T. (2017). Three-dimensional Scapular Kinematics During Arm Elevation in Massive Rotator Cuff Tear Patients. *Progress in Rehabilitation Medicine*, *2*, 20170005. https://doi.org/10.2490/prm.20170005

Morrison, S., & Newell, K. M. (2012). Aging, Neuromuscular Decline, and the Change in Physiological and Behavioral Complexity of Upper-Limb Movement Dynamics. *Journal of Aging Research*, *2012*, 891218. https://doi.org/10.1155/2012/891218

Muir, S. W., Corea, C. L., & Beaupre, L. (2010). EVALUATING CHANGE IN CLINICAL STATUS: RELIABILITY AND MEASURES OF AGREEMENT FOR THE ASSESSMENT OF GLENOHUMERAL RANGE OF MOTION. *North American Journal of Sports Physical Therapy : NAJSPT*, *5*(3), 98–110. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2971638/

Murphy, M. A., Sunnerhagen, K. S., Johnels, B., & Willén, C. (2006). Three-dimensional kinematic motion analysis of a daily activity drinking from a glass: A pilot study. *Journal of NeuroEngineering and Rehabilitation*, *3*(1), 18. https://doi.org/10.1186/1743-0003-3-18

Murphy, M. A., Willén, C., & Sunnerhagen, K. S. (2011). Kinematic Variables Quantifying Upper-Extremity Performance After Stroke During Reaching and Drinking From a Glass. *Neurorehabilitation and Neural Repair*, *25*(1), 71–80. https://doi.org/10.1177/1545968310370748

Namdari, S., Yagnik, G., Ebaugh, D. D., Nagda, S., Ramsey, M. L., Williams, G. R., & Mehta, S. (2012). Defining functional shoulder range of motion for activities of daily living. *Journal of Shoulder and Elbow Surgery*, *21*(9), 1177–1183. https://doi.org/10.1016/j.jse.2011.07.032

Ogston, J. B., & Ludewig, P. M. (2007). Differences in 3-Dimensional Shoulder Kinematics between Persons with Multidirectional Instability and Asymptomatic Controls. *The American Journal of Sports Medicine*, *35*(8), 1361–1370. https://doi.org/10.1177/0363546507300820

Petuskey, K., Bagley, A., Abdala, E., James, M. A., & Rab, G. (2007). Upper extremity kinematics during functional activities: Three-dimensional studies in a normal pediatric population. *Gait & Posture*, *25*(4), 573–579. https://doi.org/10.1016/j.gaitpost.2006.06.006

Rab, G., Petuskey, K., & Bagley, A. (2002). A method for determination of upper extremity kinematics. *Gait & Posture*, *15*(2), 113–119. https://doi.org/10.1016/S0966-6362(01)00155-2

Ramachandran, M., & Nunn, T. (2018). *Basic Orthopaedic Sciences* (M. Ramachandran, Ed.; 2nd ed.). CRC Press. https://doi.org/10.1201/9781315117294

Reddy, A. S., Mohr, K. J., Pink, M. M., & Jobe, F. W. (2000). Electromyographic analysis of the deltoid and rotator cuff muscles in persons with subacromial impingement. *Journal of Shoulder and Elbow Surgery*, *9*(6), 519–523. https://doi.org/10.1067/mse.2000.109410

Richards, R. R., An, K. N., Bigliani, L. U., Friedman, R. J., Gartsman, G. M., Gristina, A. G., Iannotti, J. P., Mow, V. C., Sidles, J. A., & Zuckerman, J. D. (1994). A standardized method for the assessment of shoulder function. *Journal of Shoulder and Elbow Surgery*, *3*(6), 347–352. https://doi.org/10.1016/S1058-2746(09)80019-0

Richardson, R. T., Nicholson, K. F., Rapp, E. A., Johnston, T. E., & Richards, J. G. (2016). A comparison of acromion marker cluster calibration methods for estimating scapular kinematics during upper extremity ergometry. *Journal of Biomechanics*, *49*(7), 1255–1258. https://doi.org/10.1016/j.jbiomech.2016.02.052

Roh, Y. H. (2013). Clinical evaluation of upper limb function: Patient's impairment, disability and health-related quality of life. *Journal of Exercise Rehabilitation*, *9*(4), 400–405. https://doi.org/10.12965/jer.130060

Roren, A., Fayad, F., Roby-Brami, A., Revel, M., Fermanian, J., Poiraudeau, S., Robertson, J., & Lefevre-Colau, M.-M. (2013). Precision of 3D scapular kinematic measurements for analytic arm movements and activities of daily living. *Manual Therapy*, *18*(6), 473–480. https://doi.org/10.1016/j.math.2013.04.005

Roren, A., Lefevre-Colau, M.-M., Roby-Brami, A., Revel, M., Fermanian, J., Gautheron, V., Poiraudeau, S., & Fayad, F. (2012). Modified 3D scapular kinematic patterns for activities of daily living in painful shoulders with restricted mobility: A comparison with contralateral unaffected shoulders. *Journal of Biomechanics*, *45*(7), 1305–1311. https://doi.org/10.1016/j.jbiomech.2012.01.027

Roy, J.-S., Moffet, H., Hébert, L. J., St-Vincent, G., & McFadyen, B. J. (2007). The reliability of three-dimensional scapular attitudes in healthy people and people with shoulder impingement syndrome. *BMC Musculoskeletal Disorders*, *8*(1), 49. https://doi.org/10.1186/1471-2474-8-49

Roy, J.-S., Moffet, H., & McFadyen, B. J. (2008). Upper limb motor strategies in persons with and without shoulder impingement syndrome across different speeds of movement. *Clinical Biomechanics*, *23*(10), 1227–1236. https://doi.org/10.1016/j.clinbiomech.2008.07.009

Rundquist, P. J., Obrecht, C., & Woodruff, L. (2009). Three-Dimensional Shoulder Kinematics to Complete Activities of Daily Living. *American Journal of Physical Medicine & Rehabilitation*, *88*(8), 623–629. https://doi.org/10.1097/PHM.0b013e3181ae0733

Schenkman, M., & Rugo de Cartaya, V. (1987). Kinesiology of the Shoulder Complex. *Journal of Orthopaedic & Sports Physical Therapy*, *8*(9), 438–450. https://doi.org/10.2519/jospt.1987.8.9.438

Schnorenberg, A. J., French, M. E., Riebe, J. M., Grindel, S. I., & Slavens, B. A. (2022). Shoulder complex kinematics pre- and post- rotator cuff repair. *Journal of Electromyography and Kinesiology*, *62*, 102331. https://doi.org/10.1016/j.jelekin.2019.07.001

Scibek, J. S., Carpenter, J. E., & Hughes, R. E. (2009). Rotator Cuff Tear Pain and Tear Size and Scapulohumeral Rhythm. *Journal of Athletic Training*, *44*(2), 148–159. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2657030/

Šenk, M., & Chèze, L. (2006). Rotation sequence as an important factor in shoulder kinematics. *Clinical Biomechanics*, *21*, S3–S8. https://doi.org/10.1016/j.clinbiomech.2005.09.007

Sheikhzadeh, A., Yoon, J., Pinto, V. J., & Kwon, Y. W. (2008). Three-dimensional motion of the scapula and shoulder during activities of daily living. *Journal of Shoulder and Elbow Surgery*, *17*(6), 936–942. https://doi.org/10.1016/j.jse.2008.04.008

Shinozaki, N., Sano, H., Omi, R., Kishimoto, K. N., Yamamoto, N., Tashiro, M., & Itoi, E. (2014). Differences in muscle activities during shoulder elevation in patients with symptomatic and asymptomatic rotator cuff tears: Analysis by positron emission tomography. *Journal of Shoulder and Elbow Surgery*, *23*(3), e61–e67. https://doi.org/10.1016/j.jse.2013.06.009

Shoukri, M. M., Colak, D., Kaya, N., & Donner, A. (2008). Comparison of two dependent within subject coefficients of variation to evaluate the reproducibility of measurement devices. *BMC Medical Research Methodology*, *8*(1), 24. https://doi.org/10.1186/1471-2288-8-24

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: Uses in assessing rater reliability. *Psychological Bulletin*, *86*(2), 420–428. https://doi.org/10.1037/0033-2909.86.2.420

Silva, C., Ferreira, J., & Parente, M. (2021). Biomechanical study of the shoulder joint complex and associated injuries. *Journal of Computation and Artificial Intelligence in Mechanics and Biomechanics*, *1*(2), 48–57. https://doi.org/10.5281/zenodo.4843511

Streiner, D. L., Norman, G. R., & Cairney, J. (2024). *Health Measurement Scales: A practical guide to their development and use*. Oxford University Press.

Struyf, F., Cagnie, B., Cools, A., Baert, I., Brempt, J. V., Struyf, P., & Meeus, M. (2014). Scapulothoracic muscle activity and recruitment timing in patients with shoulder impingement symptoms and glenohumeral instability. *Journal of Electromyography and Kinesiology*, *24*(2), 277–284. https://doi.org/10.1016/j.jelekin.2013.12.002

Thigpen, C. A., Gross, M. T., Karas, S. G., Garrett, W. E., & Yu, B. (2005). The Repeatability of Scapular Rotations Across Three Planes of Humeral Elevation. *Research in Sports Medicine*, *13*(3), 181–198. https://doi.org/10.1080/15438620500222489

Valevicius, A. M., Jun, P. Y., Hebert, J. S., & Vette, A. H. (2018). Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review. *Journal of Electromyography and Kinesiology*, *40*, 1–15. https://doi.org/10.1016/j.jelekin.2018.02.011

van Andel, C. J., Wolterbeek, N., Doorenbosch, C. A. M., Veeger, D. (H. E. J.), & Harlaar, J. (2008). Complete 3D kinematics of upper extremity functional tasks. *Gait & Posture*, *27*(1), 120–127. https://doi.org/10.1016/j.gaitpost.2007.03.002

van Andel, C.J., van Hutten, K., Eversdijk, M., Veeger, D., & Harlaar, J. (2009). Recording scapular motion using an acromion marker cluster. *Gait & Posture*, *29*(1), 123–128. https://doi.org/10.1016/j.gaitpost.2008.07.012

van den Noort, J. C., Wiertsema, S. H., Hekman, K. M. C., Schönhuth, C. P., Dekker, J., & Harlaar, J. (2014). Reliability and precision of 3D wireless measurement of scapular kinematics. *Medical & Biological Engineering & Computing*, *52*(11), 921–931. https://doi.org/10.1007/s11517-014-1186-2

Vanezis, A., Robinson, M. A., & Darras, N. (2015). The reliability of the ELEPAP clinical protocol for the 3D kinematic evaluation of upper limb function. *Gait & Posture*, *41*(2), 431–439. https://doi.org/10.1016/j.gaitpost.2014.11.007

Veeger, H. E. J., & van der Helm, F. C. T. (2007). Shoulder function: The perfect compromise between mobility and stability. *Journal of Biomechanics*, *40*(10), 2119–2129. https://doi.org/10.1016/j.jbiomech.2006.10.016

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research*, *19*(1), 231–240. https://doi.org/10.1519/15184.1

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed). Wiley.

Wu, G., van der Helm, F. C., Veeger, H. E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A. R., McQuade, K., Wang, X., Werner, F. W., & Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *J Biomech*, *38*(5), 981–992. http://0.241.195.168

Wylie, J. D. (2014). Functional outcomes assessment in shoulder surgery. *World Journal of Orthopedics*, *5*(5), 623. https://doi.org/10.5312/wjo.v5.i5.623

Xu, X., Dickerson, C. R., Lin, J., & McGorry, R. W. (2016). Evaluation of regression-based 3-D shoulder rhythms. *Journal of Electromyography and Kinesiology*, *29*, 28–33. https://doi.org/10.1016/j.jelekin.2015.07.005

Yildiz, T. I., Eraslan, L., Demirci, S., Kara, D., Ulusoy, B., Turgut, E., & Duzgun, I. (2020). The repeatability of 3-dimensional scapular kinematic analysis during bilateral upper extremity movements. *Journal of Bodywork and Movement Therapies*, *24*(4), 37–42. https://doi.org/10.1016/j.jbmt.2020.06.038

Appendix A: Informed Consent Form

Consent Form

Project title: Dalhousie Shoulder Function Test: A Reliability Study

Research Team:

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We invite you to take part in a research study being conducted by, Ms. Jiaxin Hu, who is a master student, Dr. Kathleen Maclean, an instructor, Dr. Michel Ladouceur, a professor in Kinesiology at Dalhousie University. Choosing whether or not to take part in this research is entirely your choice. There will be no impact on your studies/your employment/your performance evaluation or the services you receive if you decide not to participate in the research. The information below tells you about what is involved in the research, what you will be asked to do and about any benefit, risk, inconvenience or discomfort that you might experience.
You should discuss any questions you have about this study with Jiaxin Hu. Please ask as many questions as you like. If you have questions later, please contact Jiaxin Hu.

Purpose and Outline of the Research Study

The purpose of this study is to determine the day-to-day reliability of a biomechanical evaluation of shoulder function. We want to find out what upper limb tasks provide the most repeatable and important measures of healthy shoulder motion and muscle activity. We also want to measure the motion and muscle activity of healthy young adults. This data can be used to compare to older individuals and those with shoulder injuries.

There are currently a lot of different approaches to measuring the function of the shoulder. As a result, it is not clear which approaches provide the most useful information about what healthy shoulder function is, and how to detect and treat common shoulder injuries and diseases. We would like to determine what upper limb measures and activities provide the best information about how your shoulder performs typical daily activities, like brushing your hair, holding an item in your hand, or reaching for something overhead. We are also trying to determine what daily tasks provide the most complete information about the shoulder. It is possible that some of the tasks included in this study will measure very similar things about the shoulder. If that is the case, then both tasks do not need to be included as part of an assessment of the shoulder.

Therefore, from all the tasks measured in this study, we hope to identify a small group of upper limb tasks that can be used as a standardized shoulder assessment tool. This assessment tool can then be used to measure other groups of people, like those with shoulder injuries and diseases. We also want to use your muscle activity and upper limb motion to better understand how a young, healthy person performs these tasks. Your data can then be used to understand how people change their shoulder muscle activity or movement as they age, or become injured.

Who Can Take Part in the Research Study

In order to participate you must:

- Be between 18 – 30 years old
- Scored ≥ 90% on the Western Ontario Rotator Cuff (WORC) Index total scores
- Answer ‘No’ to all the Musculo-Skeletal Health Screening questions.

We expect twenty people will participate in this study throughout the Halifax region of Nova Scotia.

What You Will Be Asked to Do

Before your first visit to the lab, the research team will review screening questions with you without asking you to state your answers. You will be requested to complete the WORC questionnaire to determine if you have potential symptom, signs and functional limitations associated with rotator cuff pathology. If you answered ‘no’ to all the screening questions in Musculo-skeletal Health Screening questions and scored ≥ 90% on total scores of WORC, you may be eligible to participate in the study.

If you decide to participate in this research, you will be asked to make two visits to BEN lab located at Room 217 of Dalplex (6260 South St, Halifax, Nova Scotia). At both visits, the same experimental procedures will occur. Each visit will take approximately 2 hours.

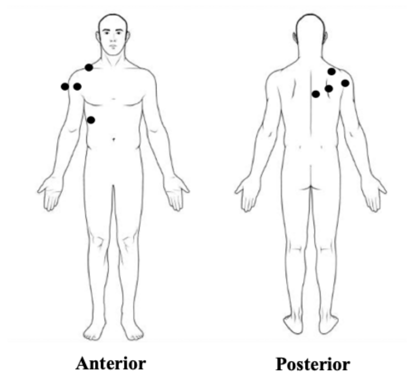
When you arrive at BEN lab on your testing day, the research team will explain all the equipment and procedures used for the study, review this form with you and answer any questions you have. During the first visit, you will be asked to sign this Informed Consent document.

Once the Informed Consent is signed, you will be asked to change into the appropriate clothing – tank top/sport bra for the study. This is because the tight-fitting athletic top can prevent obstruction of the equipment while the electrodes and markers are placed on your muscles and bony landmarks. If you do not have any of these items, they will be provided.

Descriptive Measurements:
Following completion of changing into tight-fit clothes, we will measure your: (1) height, (2) body mass and also, record your (3) sex and (4) operational hand. As your physique, sex and operational hand may be relevant to your shoulder function and movement performance

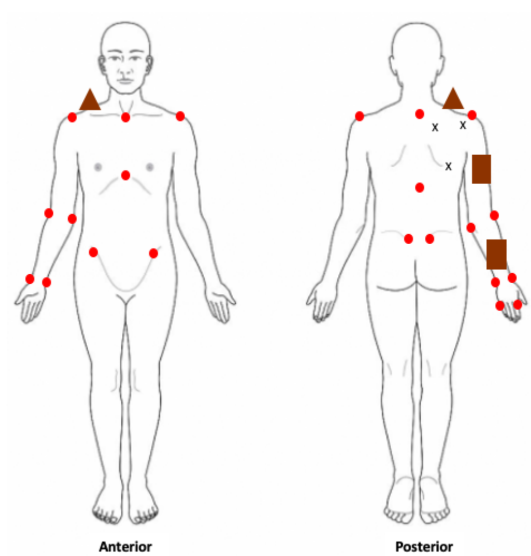
Electromyography:
Once the body measurements are done, we will prep your skin over each muscle belly by shaving hair and cleansing the tested area with an alcohol wipe. Each surface electrode will be placed over the palpated muscle belly. The specialized surface electrodes will measure your muscle activity. The surface electrodes are shown in the image below:

The following image indicates where these surface EMG electrode sensors will be placed around your shoulder and back for one side of your body. Each electrode is represented by a black dot.



Motion Capture System:
After the placement of surface electromyography electrodes, motion capture markers will then be placed over anatomical landmarks and calibration trials will be collected. Motion capture markers will be placed on your hands, forearms, upper arms, waist, chest, shoulders, and trunk to help us record your upper extremities movements. and the motion capture markers track the motion of your limbs, shoulders and trunk. The motion capture markers are shown in the image below:

To track your movement patterns, 16 retroreflective markers and marker clusters will be placed on your body landmarks on your operational limb. The placement of these markers are shown in the image below:



Upper Limb Tasks:
After application of electrodes and markers, a static calibration trial will be collected. This will require you to stand quietly in anatomical position, you will stand upright and facing forward with your arms at your side and your palms also facing forward, for 5 seconds. After this trial, the three markers on the scapula will be removed.

You will then be asked to perform a series of trials of nine different functional upper extremity tasks, listed below. The two range of motion tasks have two task levels with different hand weights.
The order of the tasks will be block randomized.

Range of Motion Test	**Experimental Task**
Anterior reach range of motion	Seated, elbow extended, arm lowered at side, elevate arm in front of the body as high as possible with: • No hand weight • 0.5kg hand weight
Lateral reach range of motion	Seated, elbow extended, arm lowered at side, elevate arm at the side of the body as high as possible with: • No hand weight • 0.5kg hand weight
Activity of Daily Living	**Experimental Task**
Drinking from a cup	Starting with hand resting in lap, raise hand toward mouth
Tuck in shirt	Starting with hand resting in lap, reach small of the back
Hook a bra/wash back	Starting with hand resting in lap, reach middle of the back
Brush hair/Put on hat	Starting with hand resting in lap, reach back of the head
Moving household items	Lift 0.5kg from hip to shoulder height
Moving household items	Lift 0.5g from hip to overhead height
Moving household items	Lift 0.5kg from right-side to left-side, over obstacle

You will be asked to complete five trials of each different task. You will be asked your Rating of Perceived Discomfort (RPD), on a scale of 0-10 (0 being no discomfort, 10 being the worst discomfort) after each trial to assess discomfort and pain. You will be given rest between each trial, as needed.

Maximum Voluntary Muscle Exertions:
After completion of the functional task trials, you will be asked to perform exertions where you push as hard as you can against resistance for all eight muscles. Each exertion is 5-seconds in duration. These exertions are designed to determine your maximal output for each of the muscles being examined. You will be given verbal encouragement while attempting to maximize your exertion.

You are free to withdraw from the study at any point during the protocol. When the study is finished or if you decide to stop participating, you will not be required to do anything further.

Video:
To confirm your upper limb movement, video will also be taken when you perform shoulder functional tasks. One of ten mounted motion capture cameras will be set as video mode. Video will not be taken between trials, or during practice trials. No audio will be recorded.

Video data files will be named using participant identification codes and immediately transferred to the password encrypted data collection computer following each data collection. Video data will only be used to verify participants' movements while performing functional tasks. Video data will never be used for further analysis or in journal articles or conferences.

Possible Benefits, Risks and Discomforts:
Participating in the study might not benefit you directly, but the results of this study will increase our understanding of shoulder motion and function. This may benefit individuals with shoulder pathology by providing better shoulder function quantification, mobility impairments detection and therapeutic interventions. If you are interested in learning about your movements, we can provide you with information upon request. You may also learn about experimental methodologies and procedures commonly used in biomechanics and human movement research.

The risks associated with this study are minimal; there are no known risks for participating in this research beyond

1) Fatigue: your visiting to the testing site will take approximately 2 hours of your time. Participants may become fatigued by the protocol, but ample rest time will be provided, as needed, throughout the protocol.
   The maximum voluntary contractions may result in some muscle soreness. However, this will be no different than that experienced during typical exercise and should resolve within 1-2 days.
   The research team will check-in with you after every movement task and maximum voluntary contraction to assess your comfort, fatigue, and perceived exertions. You will be provided with short rest period between each movement task. If you feel the movement tasks are too difficult, and/or suffer

prolonged muscle soreness or any discomfort, you may stop the data collection, decline to perform any more trials, or withdraw from the study, at any time. If an injury or adverse event occurs within the lab, the standard Emergency Response Plan for the Dalplex will be implemented. For an injury, the study will be halted. If necessary, emergency protocols including contacting Dalhousie Security, who will direct emergency services to our location.

2) Equipment placement and removal: Hypoallergenic adhesive stickers will be used to attach motion analysis and muscle activity devices to the body. These may cause minor discomfort when removed. Any redness from the adhesives should resolved within 1-2 days.

Compensation / Reimbursement

There is no compensation for being part of this research study. We will reimburse you for out-of- pocket transportation-related expenses you incur because of participating in this study (e.g. city transportation or parking). These expenses will be reimbursed following completion of each testing site visit. The maximum amount of reimbursement is $10 per visit. **The proof of transportation/parking costs will not be required for you to be reimbursed.**

How your information will be protected:

The people who work with your information have special training and an obligation to keep all research information private. Your participation in this research will be known only to the research team at Dalhousie University. We will describe and share our findings in progress reports, class presentations and written thesis. We may also submit our findings for publication to an academic journal. We will be very careful to only talk about group results so that no one will be identified. This means that *you will not be identified in any way in our reports*. All your identifying information such as your name and contact information will be securely stored separately from your research information. We will use a participant number (not your name) in our written and computer records so that the research information we have about you contains no names. During the study, all electronic records will be kept secure in an encrypted file on the researcher's password-protected computer. All paper records will be kept secure in a locked filing cabinet located in the researcher's office.

If you choose to withdraw from this study, all of your personal information collected will be destroyed (i.e. paper copies shredded, and electronic files permanently deleted). The written informed consent documents will be stored in a cabinet within the Dalplex with only the principal investigator having direct access. All electronic data will be stored on password encrypted computers. To ensure confidentiality of your information, you will be assigned an identification code under which all data will be labeled and stored. One formal master list of participants' names will be compiled and kept safe by Dr. Ladouceur on a password encrypted computer. The master tracking list that including personal identifiable information will be destroyed one month after testing.

You will have the right to review and remove your data or have it destroyed before the data have been analyzed and presented. The principal investigator will keep all sensitive materials (questionnaires, informed consent forms) collected during this research project for 5 years after the release of the results of this study. After that, data and materials will be destroyed (i.e. paper copies shredded, and electronic files permanently deleted). You will be given the opportunity to ask questions to enhance your learning experience. If you wish to know the results of the study, you may contact the principal investigator.

If You Decide to Stop Participating

You are free to leave the study at any time. If you decide to stop participating during the study, you can decide whether you want any of the information that you have provided up to that point to be removed or if you will allow us to use that information. After participating in the study, you can decide for up to 1 month if you want us to remove your data. After that time, it will become impossible for us to remove it because it will already be published/ analyzed/ anonymized.

The Dalhousie University Research Ethics Board or the Principal Investigator has the right to stop participant recruitment or cancel the study at any time.
Lastly, the principal investigator may decide to remove you from this study without your consent for any of the following reasons:

- You do not follow the directions of the Principal Investigator;
- In the opinion of the Principal Investigator you are experiencing side effects that are harmful to your health or well-being;
- There is new information that shows that being in this study is not in your best interests;

If you are withdrawn from this study, a member of the study team/principal investigator will discuss the reasons with you.

How to Obtain Results

You can obtain these results by including your contact information at the end of the signature page and we will send them to you via your preferred method.

Questions

We are happy to talk with you about any questions or concerns you may have about your participation in this research study. Please contact Ms. Jiaxin Hu at jx684666@dal.ca or Dr. Michel Ladouceur at 902 494-2754, Michel.Ladouceur@dal.ca at any time with questions, comments, or concerns about the research study.
If you have any ethical concerns about your participation in this research, you may also contact Research Ethics, Dalhousie University at (902) 494-3423, or email: ethics@dal.ca.

Others

Conflict of interests

There is a potential that a student registered in a course instructed by Dr. Kathleen Maclean, or is a fellow student of the co-investigator, Jiaxin Hu will be recruited in the study. There is also a potential that a student registered in a course in which the co-investigator is/was the student's teaching assistant (TA) will be recruited in the study. The principal investigator Dr. Kathleen Maclean will not recruit any participants for the study. Only the co-investigator Jiaxin Hu will be responsible for recruiting for this study. Co-investigator will not recruit participants that are registered in courses that are taught by Dr. Kathleen Maclean or courses in which the co-investigator is a TA. The research team are aware that all the information collected from the study is strictly confidential and under no circumstances should be discussed outside of the lab.

Participants will be reminded that their participation is completely on a voluntary basis and that no academic reward or penalty will occur whether they choose to attend the study or not. Dr. Kathleen Maclean will not be informed of potential student participants and will only has the access to participant's 8-digit ID number in the laboratory schedule.

What are my responsibilities?
As a study participant you will be expected to:

- Follow the directions of the Principal Investigator
- Report if there are any changes in your health that could affect your performance to the Principal Investigator prior to or during the data collection.
- Report any problems that you experience that you think might be related to participating in the study

What are my rights?
You have the right to receive all information that could help you make a decision about participating in this study. You also have the right to ask questions about this study and your rights as a research participant, and to have them answered to your satisfaction before you make any decision. You also have the right to ask questions and to receive answers throughout this study.

In the next part, you will be asked if you agree (consent) to join this study. If the answer is "yes", youwill need to sign the form.

Signature Page

Project Title: Dalhousie Shoulder Function Test: A Reliability Study

I have read the explanation about this study. I have been given the opportunity to discuss it and my questions have been answered to my satisfaction. I understand that I have been asked to take part in two interviews that will occur at a location acceptable to me, and that those interviews will be recorded. I understand direct quotes of things I say may be used without identifying me. I agree to take part in this study. My participation is voluntary, and I understand that I am free to withdraw from the study at any time, after my second interview is complete.

____________________________	___________________________	
Print Name of Participant	Signature	Date
____________________________	___________________________	
Print Name of Investigator	Signature	Date
____________________________	___________________________	
Witness Name	Signature	Date

Options (you can still participate in the research if you select no):

I agree to have my de-identified data included in future study ☐Yes ☐No

____________________________	___________________________	
Name	Signature	Date

Please provide an email address below if you would like to be sent a summary of the study group results.

Email address: _____________

Appendix B: Data Collection Sheet

DALHOUSIE UNIVERSITY

BEN ID:		**Session ID:**	
Date:		**Data Collectors:**	

Participant Characteristics			
Age on Day of Collection: (years)		**Sex:**	
Operational Hand:	**R L**		

Task Order	**Range of Motion Test**	**Experimental Task**	**Rating of Perceived Discomfort**
	Anterior reach range of motion	Seated, elbow extended, arm lowered at side, elevate arm in front of the body as high as possible with: • No hand weight • 0.5kg hand weight	
	Lateral reach range of motion	Seated, elbow extended, arm lowered at side, elevate arm at the side of the body as high as possible with: • No hand weight • 0.5kg hand weight	
	Activity of Daily Living	**Experimental Task**	
	Drinking from a cup	Starting with hand resting in lap, raise hand toward mouth	
	Tuck in shirt	Starting with hand resting in lap, reach small of the back	
	Hook a bra/wash back	Starting with hand resting in lap, reach middle of the back	
	Brush hair/Put on hat	Starting with hand resting in lap, reach back of the head	

Task Order	Activity of Daily Living	Experimental Task	Rating of Perceived Discomfort
	Moving household items	Lift 0.5kg from hip to shoulder height	
	Moving household items	Lift 0.5g from hip to overhead height	
	Moving household items	Lift 0.5kg from right-side to left-side, over obstacle	

DELSYS Trigno Wireless EMG System Properties (and Locations)						
Channel	**Right**	**Left**		**Channel**	**Right**	**Left**
CH1				CH9		
CH2				CH10		
CH3				CH11		
CH4				CH12		
CH5				CH13		
CH6				CH14		
CH7				CH15		
CH8				CH16		

Observational /Processing Notes

Appendix C: Email Script

Biodynamics
Ergonomics
Neuroscience
LAB

Dalhousie Shoulder Function Test: A Reliability Study

Dear______________________________,

Thank you for your interest in our study entitled: "Dalhousie Shoulder Function test: A Reliability Study", which is being conducted by Jiaxin Hu, a MSc student, Dr. Kathleen Maclean, an instructor, Dr. Michel Ladouceur, a professor in Kinesiology in the School of Health and Human Performance at Dalhousie University. Participation in the study is voluntary and you may withdraw at any time. This is a fun and engaging opportunity for you to participate in a university research study, and experience biomechanics firsthand.

In this study, we want to understand the day-to-day reliability of a biomechanical protocol of shoulder function. We will use equipment that allows us to track your movement with a three-dimensional motion capture system and your muscle activity with surface electromyography while you perform 9 different shoulder functional tasks. More specifically, we are attempting to determine the consistency and appropriateness of a biomechanical test protocol of shoulder function for future laboratory research. As well, information we collect from you will help us develop a database of healthy shoulder movements and muscle activation patterns.

To be eligible for this study you need the following:

- Be between the ages of 18 and 30
- Scored $\geq$ 90% on Western Ontario Rotator Cuff (WORC) total scores
- Answer "No" to all of the questions in the Musculo-Skeletal Health Screening questionnaire.

If you meet the inclusion criteria above and are still interested in participating, please contact Ms. Jiaxin Hu and Dr. Kathleen MacLean by replying to this e-mail with any further questions about the study. The research team will also send you the Informed Consent, Musculo-Skeletal Health Screening questionnaire and WORC questionnaire. The Musculo-skeletal Health Screening questionnaire and the WORC questionnaire need to be completed and sent back to the research team prior coming to the lab to assess your eligibility. Once your eligibility is confirmed, the research team will set up a day for you to come into BEN Lab to partake in the study.

If you DO NOT meet one of these criteria then we thank you very much for your interest in the study; however, you are ineligible to participate. If you have any further questions, please feel free to contact Ms. Jiaxin Hu by replying to this message

Before you coming to the lab, we will review the eligibility and the exclusion criteria with you. When you arrive at the BEN Lab (Dalplex 217), we will review the study with you and will ask you to sign the Informed Consent. These documents are provided to you as an attachment to this email. If you determine that you are ineligible to participate in the study, please destroy these forms (i.e., shred hard copies, delete electronic copies). The consent form only needs to be read prior to coming to BEN Lab. The consent form will be completed and signed in on the day of testing. Once the Informed Consent is signed, you will be asked to change into the appropriate clothing for the study –tight-fitting athletic tank top/sport bra. This is because the tight-fitting athletic top can prevent obstruction of the equipment while the electrodes and markers are placed on your muscles and bony landmarks. If you do not have any of these items, they will be provided.

More study information has provided in the attached information form, and you are encouraged to read it to learn more details about the study.

Thank you for considering participating in this study. This is a unique opportunity to be involved in research. If you are interested in participating, contact the BEN lab (902-494-2066 or Benlab@dal.ca) directly to make an appointment. We will contact you within the next couple of weeks.

If you have questions or need more information about this study, please do not hesitate to contact us using the information listed below.

Sincerely,
Jiaxin Hu

BEN Laboratory: Phone: 902.494.2066 Email: Benlab@dal.ca

Appendix D: Musculo-Skeletal Health Screening Questionnaire

DALHOUSIE UNIVERSITY

Biodynamics Ergonomics Neuroscience LAB

Musculo-Skeletal Health Screening Questionnaire

Question	Answer
Have you had prior surgery to either upper extremity? How long ago?	
Have you had an injury to either upper extremity? How long ago?	
Do you have any form of arthritis (i.e., rheumatic, psoriatic) or gout?	
Do you have any history of bone disease? (i.e., osteoporosis)	
Have you had back pain in the past year that has prevented you from doing activities of daily living?	
Do you have any history of neurological disease?	
Do you have any history of heart disease?	
Do you have any prior history of stroke?	
Do you have any lung or breathing problems that interfere with your ability to perform daily activities?	

Appendix E: WORC Index

THE WESTERN ONTARIO ROTATOR CUFF INDEX (WORC)

The following questions concern the **physical symptoms** you have experienced, how your shoulder has affected your **work, sports or recreational activities**, the amount that your shoulder has affected or changedyour **lifestyle**, and your **emotions** with regards to your shoulder. Please answer these questions based on how you have felt in the **past week.** For each question, enter to what degree you have experienced these factors with a **slash " / ".**

PHYSICAL SYMPTOMS

1. How much sharp pain do you experience in your shoulder?

No pain — Extreme pain

2. How much constant, nagging paindo you experience in your shoulder?

No pain — Extreme pain

3. How much weakness do you experience in your shoulder?

No weakness — Extreme weakness

4. How much stiffness do you experience in your shoulder?

No stiffness — Extreme stiffness

5. How much clicking, grinding, or crunchingdo you experience in your shoulder?

None — Extreme

6. How much discomfort do you experience inyour neck because of your shoulder?

No discomfort — Extreme discomfort

SPORTS/RECREATION

7. How much has your shoulder affectedyour fitness level?

Not affected — Extremely affected

8. How much has your shoulder affected yourability to throw hard or far?

Not affected — Extremely affected

9. How much difficulty do you have with someone or something coming in contact with your shoulder?

No fear — Extremely fearful

10. How much difficulty do you experience doingpush-ups or other strenuous shoulder exercises because of your shoulder?

No difficulty — Extreme difficulty

WORK

11. How much difficulty do you experience in dailyactivities about the house or yard?

No difficulty — Extreme difficulty

12. How much difficulty do you experience workingabove your head?

No difficulty — Extreme difficulty

13. How much do you use your uninvolved arm tocompensate for your injured one?

Not at all — Constant

14. How much difficulty do you experience lifting heavy objects from the ground or below shoulderlevel?

No difficulty — Extreme difficulty

LIFESTYLE

15. How much difficulty do you have sleepingbecause of our shoulder?

No difficulty — Extreme difficulty

16. How much difficulty have you experienced withstyling your hair because of your shoulder?

No difficulty — Extreme difficulty

17. How much difficulty do you have “roughhousingor horsing around” with family and friends?

No difficulty — Extreme difficulty

18. How much difficulty do you have dressing orundressing?

No difficulty — Extreme difficult

EMOTIONS

19. How much frustration do you feel because ofyour shoulder?

No frustration | Extreme frustration

20. How "down in the dumps" or depressed do youfeel because of your shoulder?

None | Extreme

21. How worried or concerned are you about the effect of your shoulder on you occupation or work?

Not at all | Extremely concerned

Appendix F: Hand to Head Tasks

Description of kinematic characteristics of the hand to head task by selected studies. Categories include number of markers, segments and DoFs studied, and whether a study provided instructions and followed ISB guidelines.

Functional Tasks	Authors	Participants	Methodologies	Kinematic Variables
Hand to top of head	Rab et al. (2002)	N = 48 Age = 5 – 19 years children	Shoulder flexion (+) (-20° - 100°) Shoulder abduction (+) (2° - 55°) Shoulder external rotation (+) (-45°-50°) Elbow flexion (+) (0° - 120°) ISB: no Instruction: NA 18 Anatomical markers	Joint angle trajectories
Hand to top of head & High reach above head	Petuskey et al. (2007)	N = 51 Age = 5 – 18 years children	Shoulder flexion (85°±17° vs. 142°±10°) Shoulder abduction (36°± 13° vs. 34°±9°) Shoulder internal rotation (-32°± 15° vs. -16°±24°) Elbow flexion(110°± 7° vs. 18°±6°) ISB: no Instruction: NA 18 Anatomical markers	Joint angle trajectories RoM Joint angle at point of task achievement (PTA)
Box off head-height shelf	Gates et al. (2016)	N = 15 (8 men, 7 women) Age = 26 years	TH plane of elevation (mean peak = 86°) TH elevation (mean peak = 108°) TH axial rotation (mean int. = 4° & ext. = 48°) Elbow flexion (mean peak = 120°) ISB: yes Instruction: yes Anatomical & marker cluster	Joint angle trajectories Joint angle at peak motion RoM

Functional Tasks	Authors	Participants	Methodologies	Kinematic Variables
Combing task	van Andel et al., (2008)	N = 6 males & 4 females Age = 28.5 ± 5.7 years	Scapula lateral rotation (TH) (0° - 35°) Shoulder elevation (18° - 100°) Shoulder rotations (external: 5° - 80°) Elbow flexion (mean: 122°; 20° - 145°) ISB: yes Instruction: yes Marker cluster	Joint angle trajectories RoM
Comb hair	Friesen et al. (2023)	N = 30 (15 M/F) Age = 24 ± 4 years	TH elevation TH axial rotation TH horizontal flexion Scapular internal rotation (25° - 35°) → retraction Scapular upward rotation (0° - 40°) → lateral rotation Scapular posterior tilt (0°-10°), anterior tilt (0° - 5°) ISB: yes Instruction: yes Anatomical & marker cluster	Repeatability (ICC) Joint angle trajectories

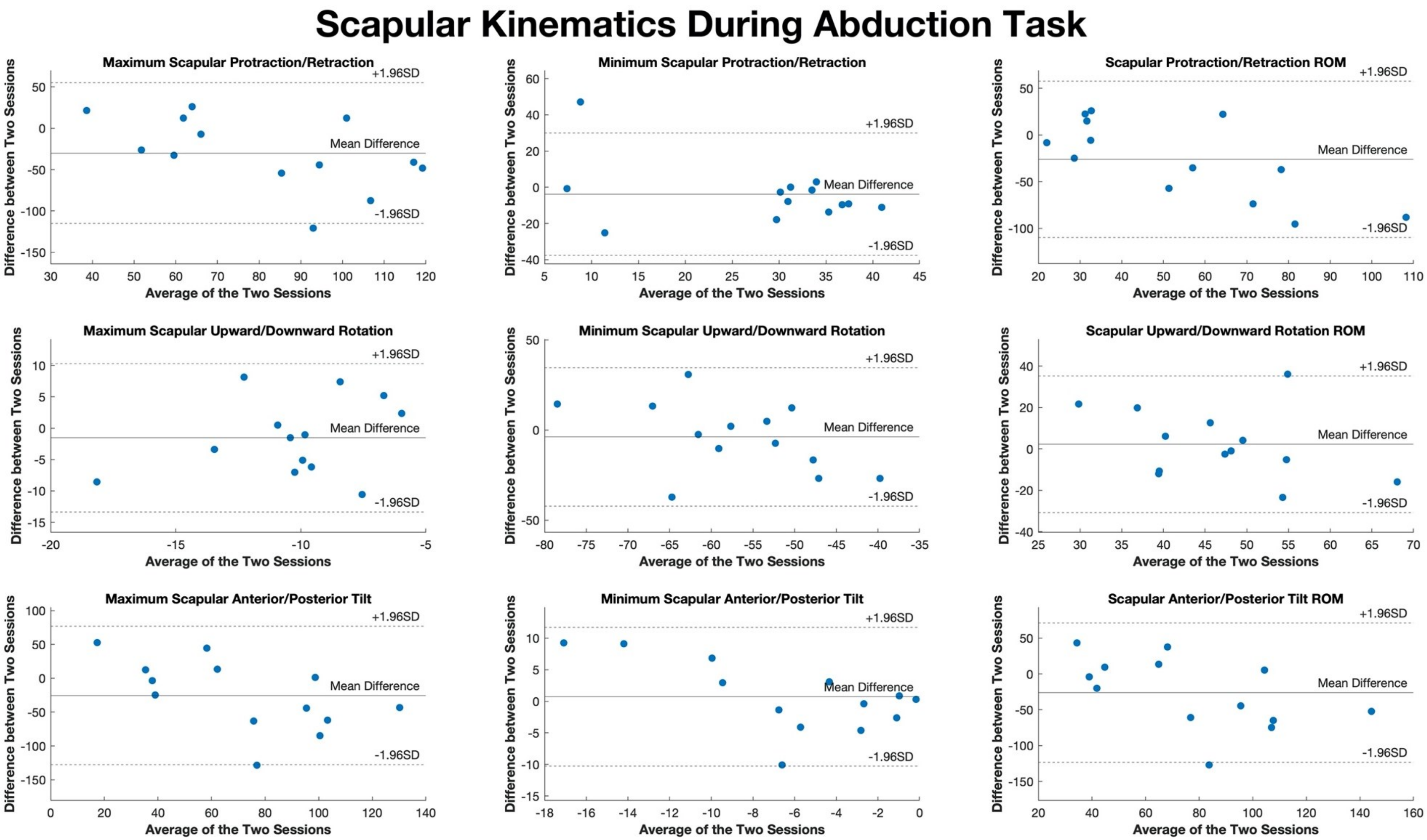
Appendix G: Hand to Back Tasks

Description of kinematic characteristics of the hand to back task by selected studies. Categories include number of markers, segments and DoFs studied, and whether a study provided instructions and followed ISB guidelines.

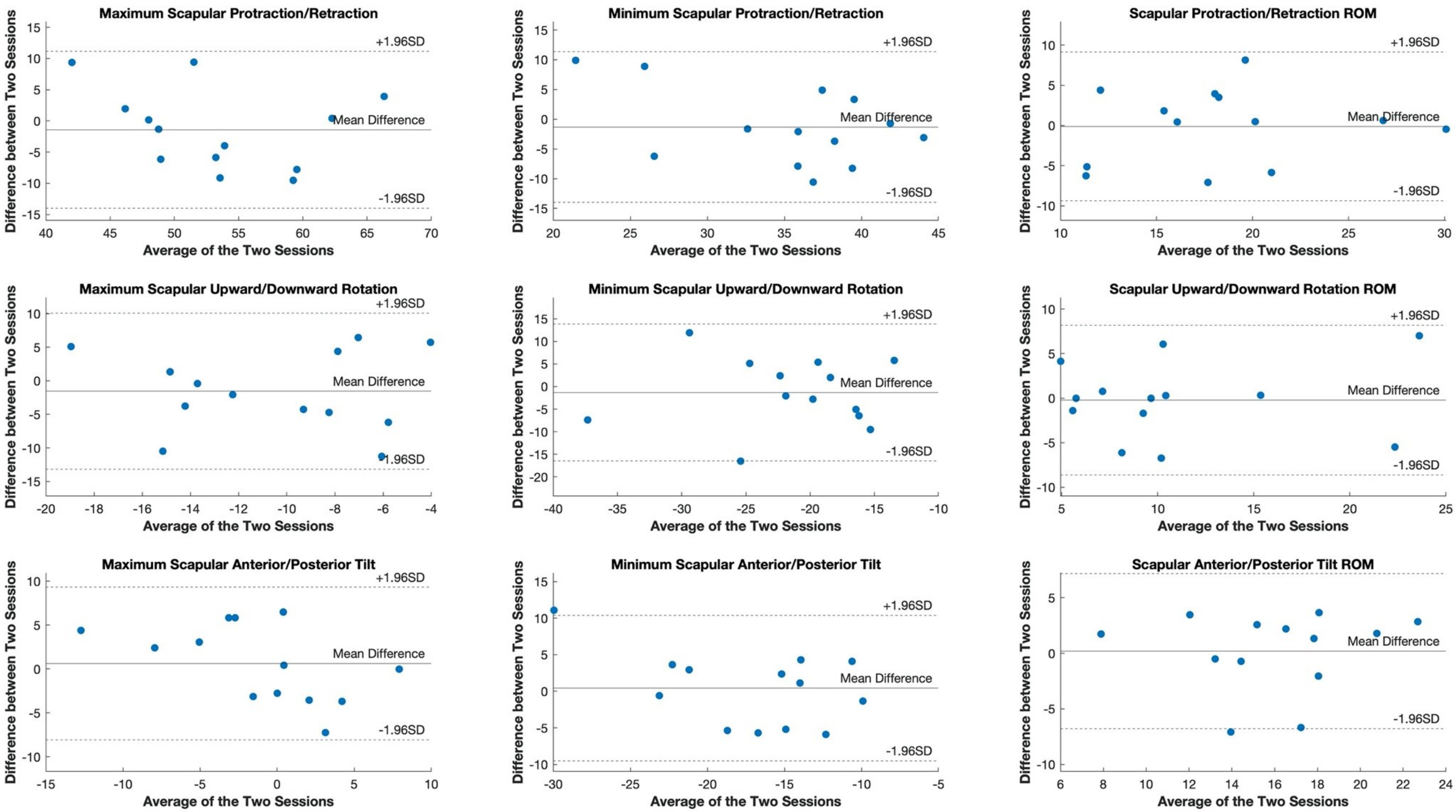
Functional Tasks	Authors	Participants	Methodologies	Kinematic Variables
Hand to ipsilateral back pocket	Petuskey et al. (2007)	Refer to the above table	TH: Shoulder extension - (-47°±11°) Shoulder abduction+ (2°±5°) Shoulder internal- rotation (-27°±11) Elbow flexion+(63°±21°) ISB: no Instruction: NA 18 Anatomical markers	Joint angle trajectories RoM Joint angle at PTA
Hand to ipsilateral back pocket	van Andel et al. (2008)	Refer to the above table	Scapula lateral rotation + (TH) (0°-5°) TH: Shoulder elevation + (25°-50°) Shoulder internal+/external-rotation (-50°-100°) Elbow flexion+/extension- (5°-100°) ISB: yes Instruction: yes Marker cluster	Joint angle trajectories RoM
Washing the back (reaching the thoracic spine as far as can)	Rundquist et al. (2009)	N = 27 (23 female & 4 male) Age = 21 – 29 years	TH plane of elevation TH angle of elevation TH internal rotation (mean=85°→ 48°to149°) GH adduction/abduction GH flexion/extension GH internal/external rotation ST internal/external rotation ST downward/upward rotation ST anterior/posterior tipping ISB: yes (TH and ST) Instruction: yes	Joint angles Regression equation

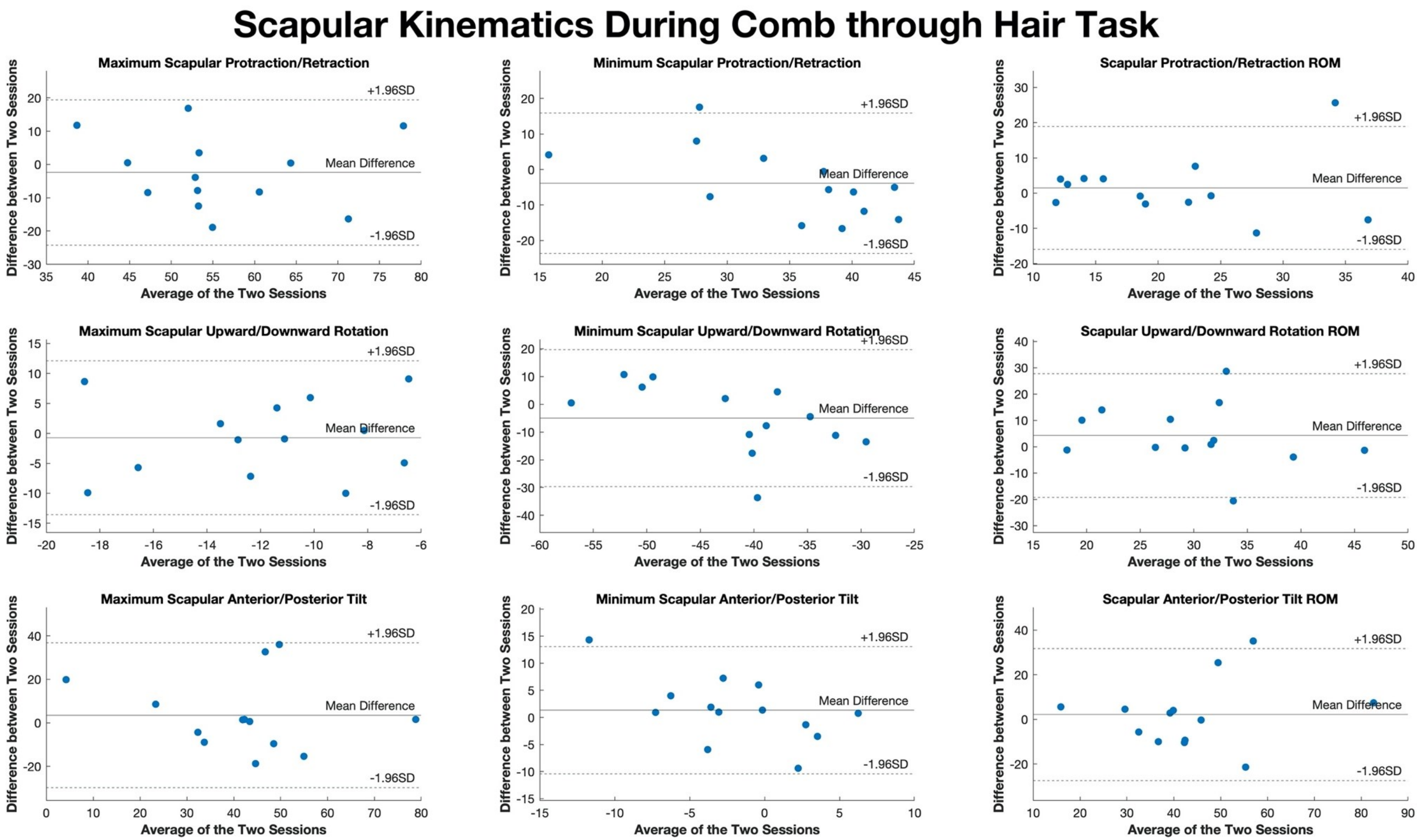
Functional Tasks	Authors	Participants	Methodologies	Kinematic Variables
Hand to ipsilateral back pocket	Vanezis et al. (2015)	N = 10 (4 males & 6 females) Age = 13.6 ± 4.3 years	ROM: Scapular protraction (8°) Scapular medial rotation (8°) Scapular posterior tilting (17°) GH plane of elevation (77°) GH elevation (16°) GH internal rotation (69°) TH: Shoulder plane of elevation (87°) Shoulder elevation (27°) Shoulder internal rotation (56°) Elbow flexion (27°) ISB: yes Instruction: NA Anatomical & marker cluster	RoM Time to completion Mean velocity Index of curvature Reliability (CMC and SEM)
Hand to ipsilateral back pocket	Gates et al. (2016)	Refer to the above table	TH plane of elevation (mean peak = -65°) TH elevation (mean peak = 80°) TH axial rotation (external: -) (-53°) Elbow flexion (mean peak = 101°) ISB: yes Instruction: yes Anatomical & marker cluster	Joint angle trajectories Joint angle at peak motion RoM
Tie apron	Friesen et al. (2023)	Refer to the above table	TH elevation (62°) TH axial rotation TH horizontal flexion Scapular internal rotation → retraction Scapular upward rotation → lateral rotation Scapular posterior/anterior tilt ISB: yes Instruction: yes	Repeatability (ICC) Joint angle trajectories

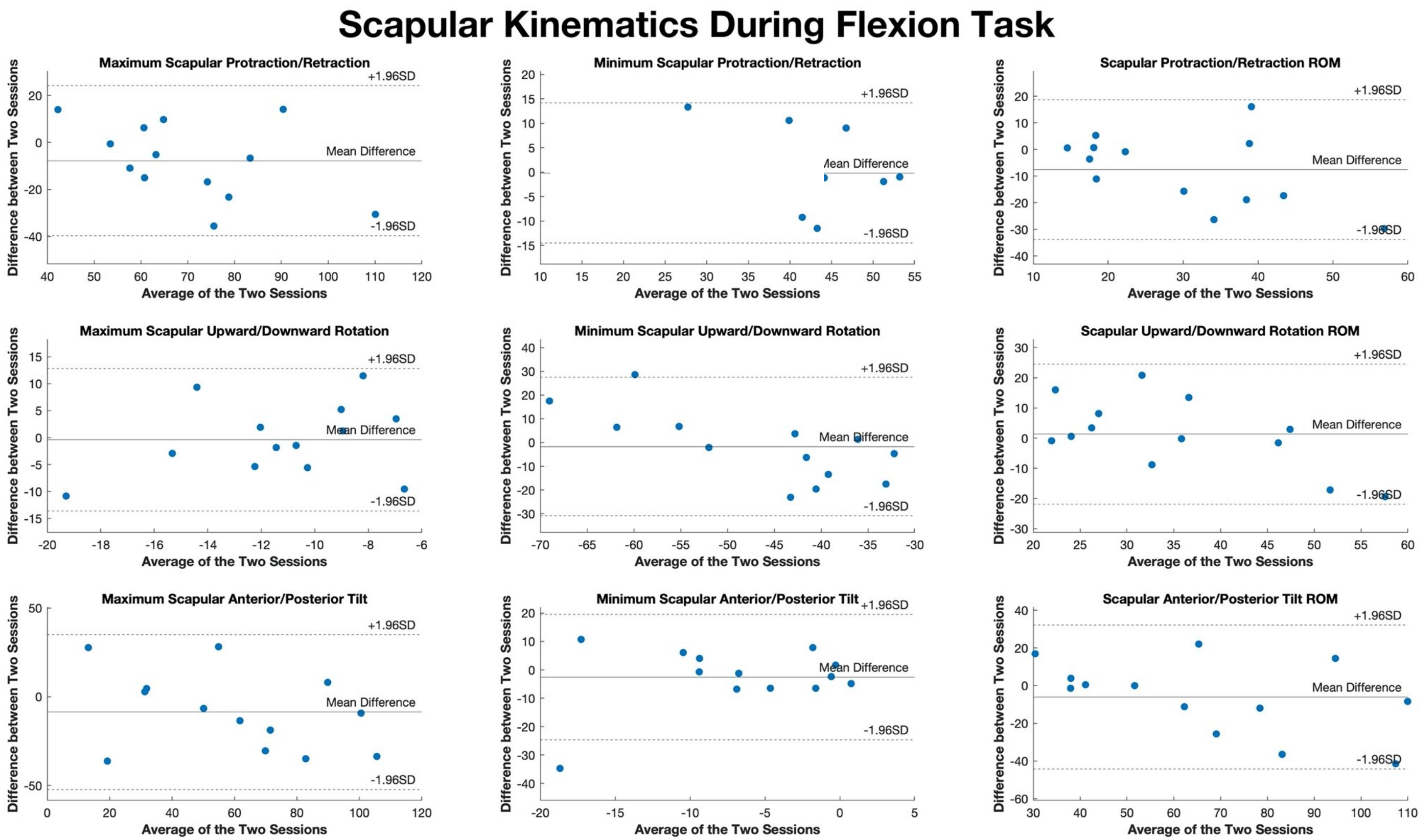
Appendix H: Bland-Altman Plot of ST Kinematics Agreement Between Two Test Sessions



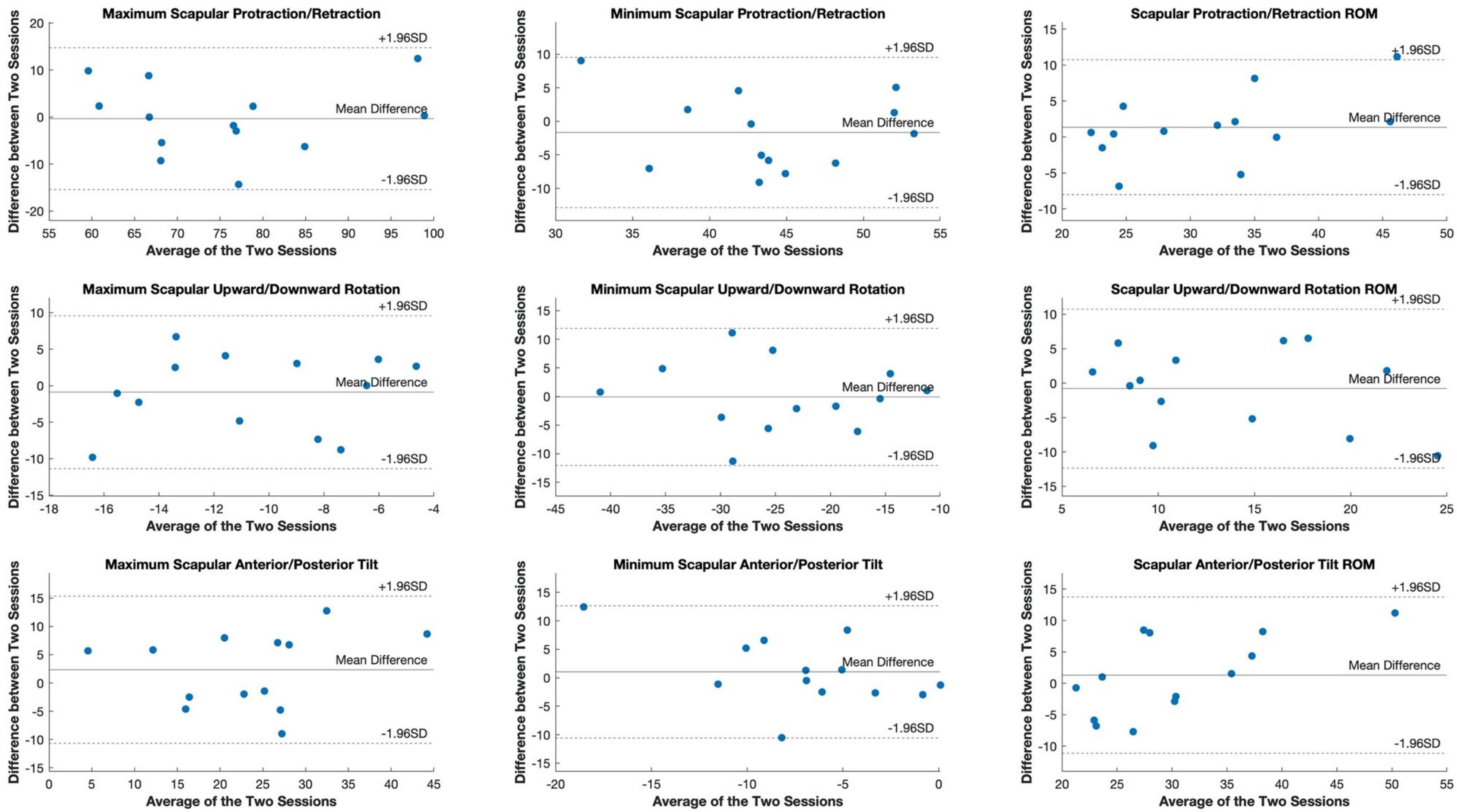
Scapular Kinematics During Tie Apron Task



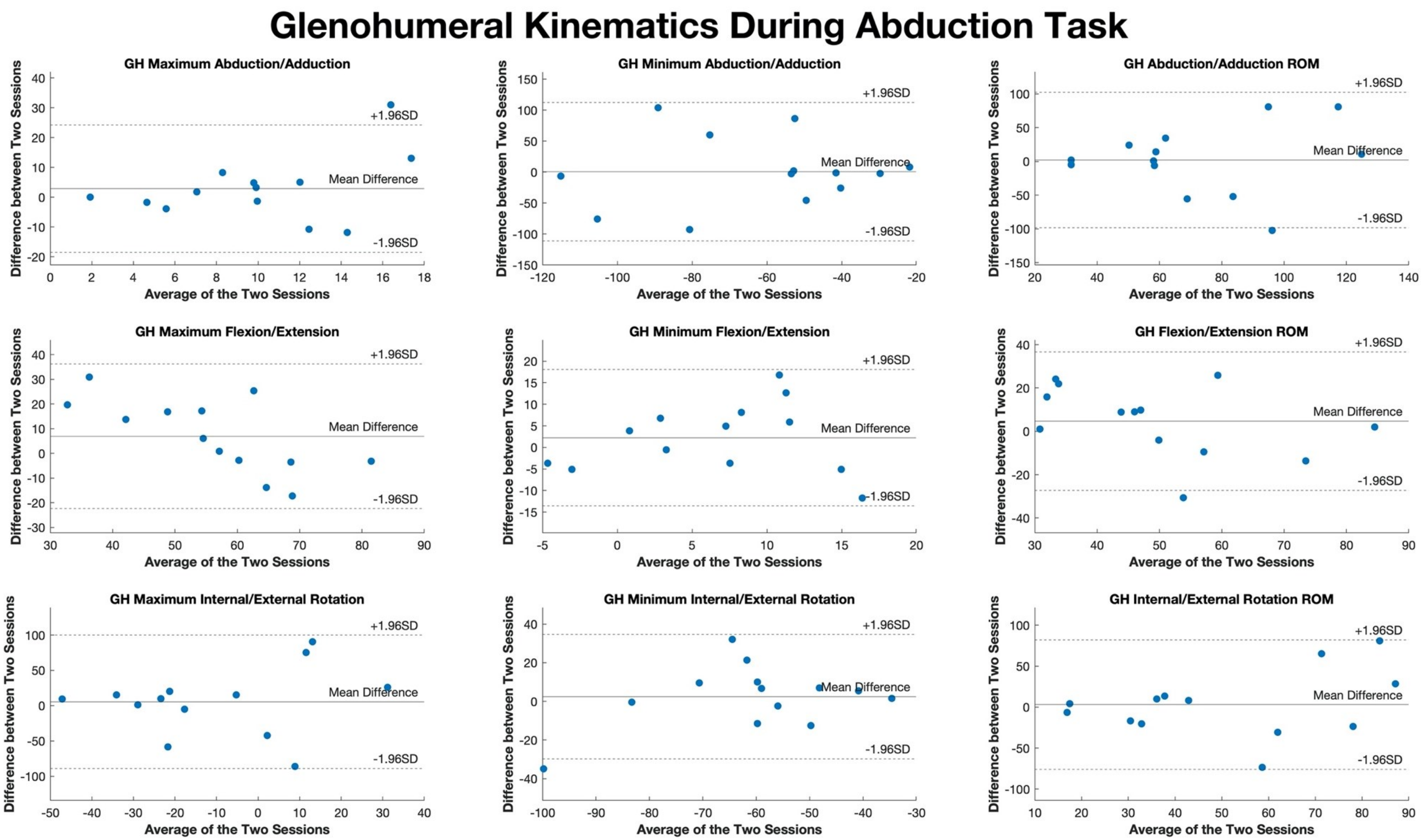

Scapular Kinematics During Comb through Hair Task
Maximum Scapular Protraction/Retraction
Minimum Scapular Protraction/Retraction
Scapular Protraction/Retraction ROM
Maximum Scapular Upward/Downward Rotation
Minimum Scapular Upward/Downward Rotation
Scapular Upward/Downward Rotation ROM
Maximum Scapular Anterior/Posterior Tilt
Minimum Scapular Anterior/Posterior Tilt
Scapular Anterior/Posterior Tilt ROM
+1.96SD
Mean Difference
-1.96SD
Difference between Two Sessions
Average of the Two Sessions


Scapular Kinematics During Flexion Task
Maximum Scapular Protraction/Retraction
Minimum Scapular Protraction/Retraction
Scapular Protraction/Retraction ROM
Maximum Scapular Upward/Downward Rotation
Minimum Scapular Upward/Downward Rotation
Scapular Upward/Downward Rotation ROM
Maximum Scapular Anterior/Posterior Tilt
Minimum Scapular Anterior/Posterior Tilt
Scapular Anterior/Posterior Tilt ROM
Difference between Two Sessions
Average of the Two Sessions
+1.96SD
Mean Difference
-1.96SD

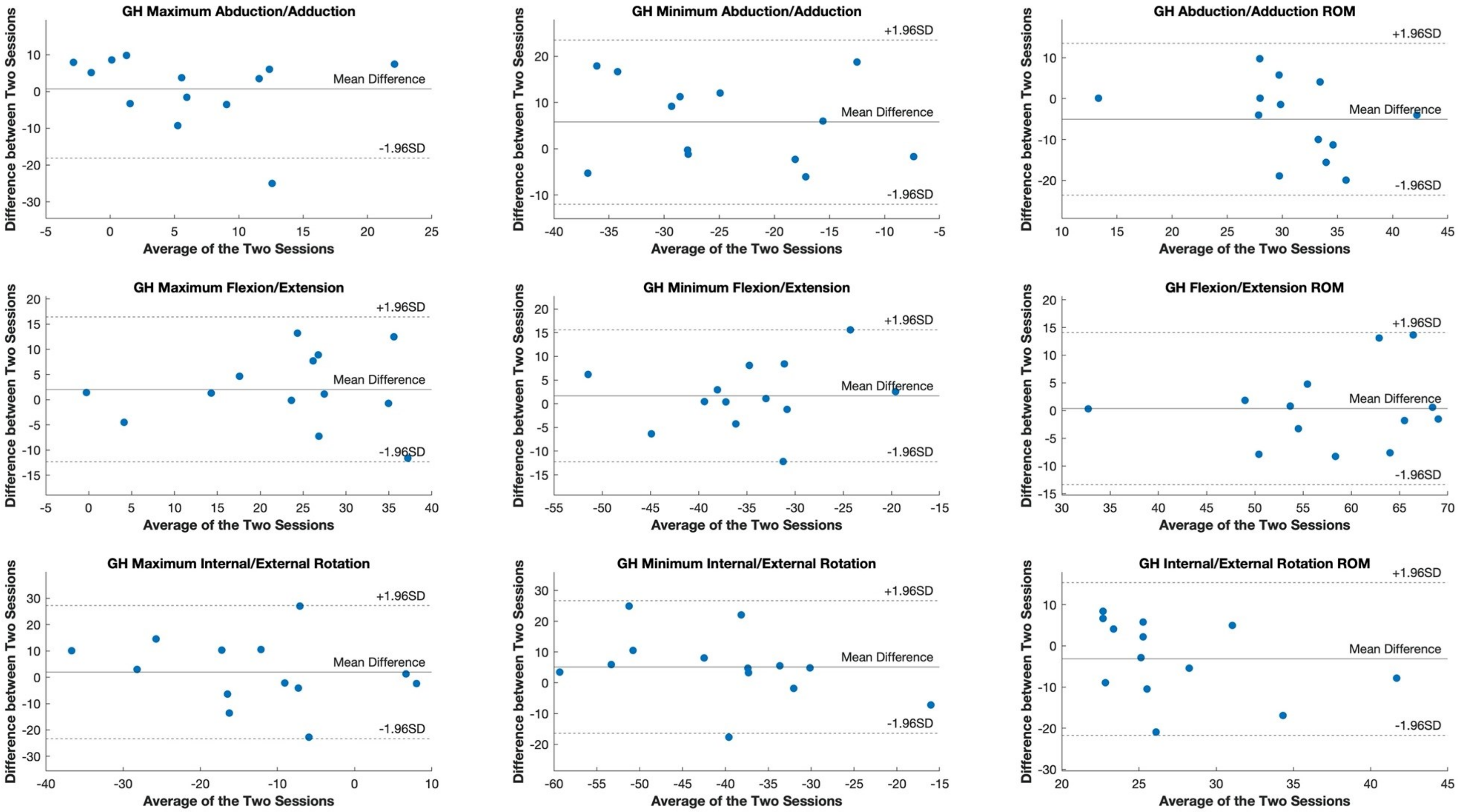
Scapular Kinematics During Floor to Shoulder Lift Task



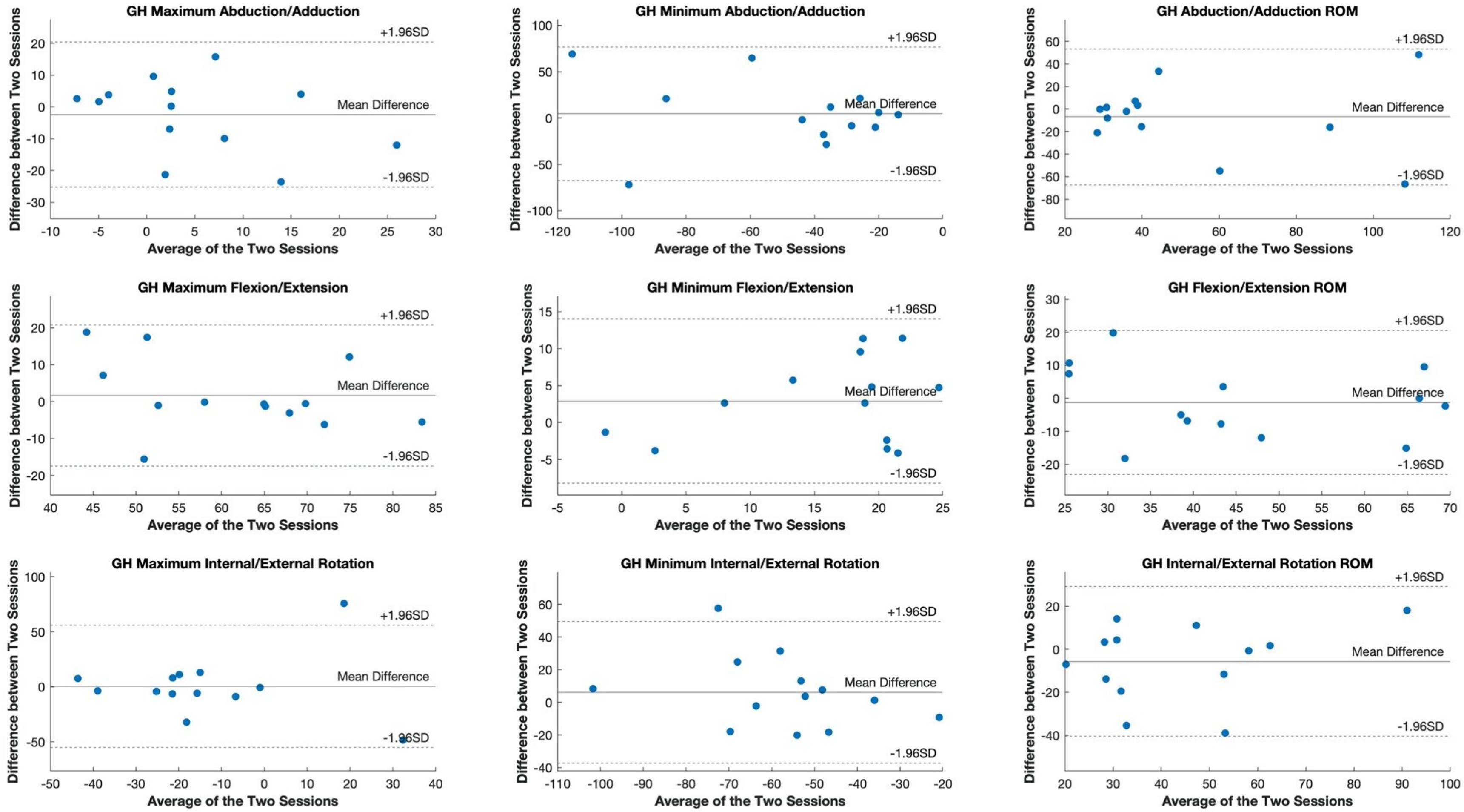
Appendix I: Bland-Altman Plot of GH Kinematics Agreement Between Two Test Sessions



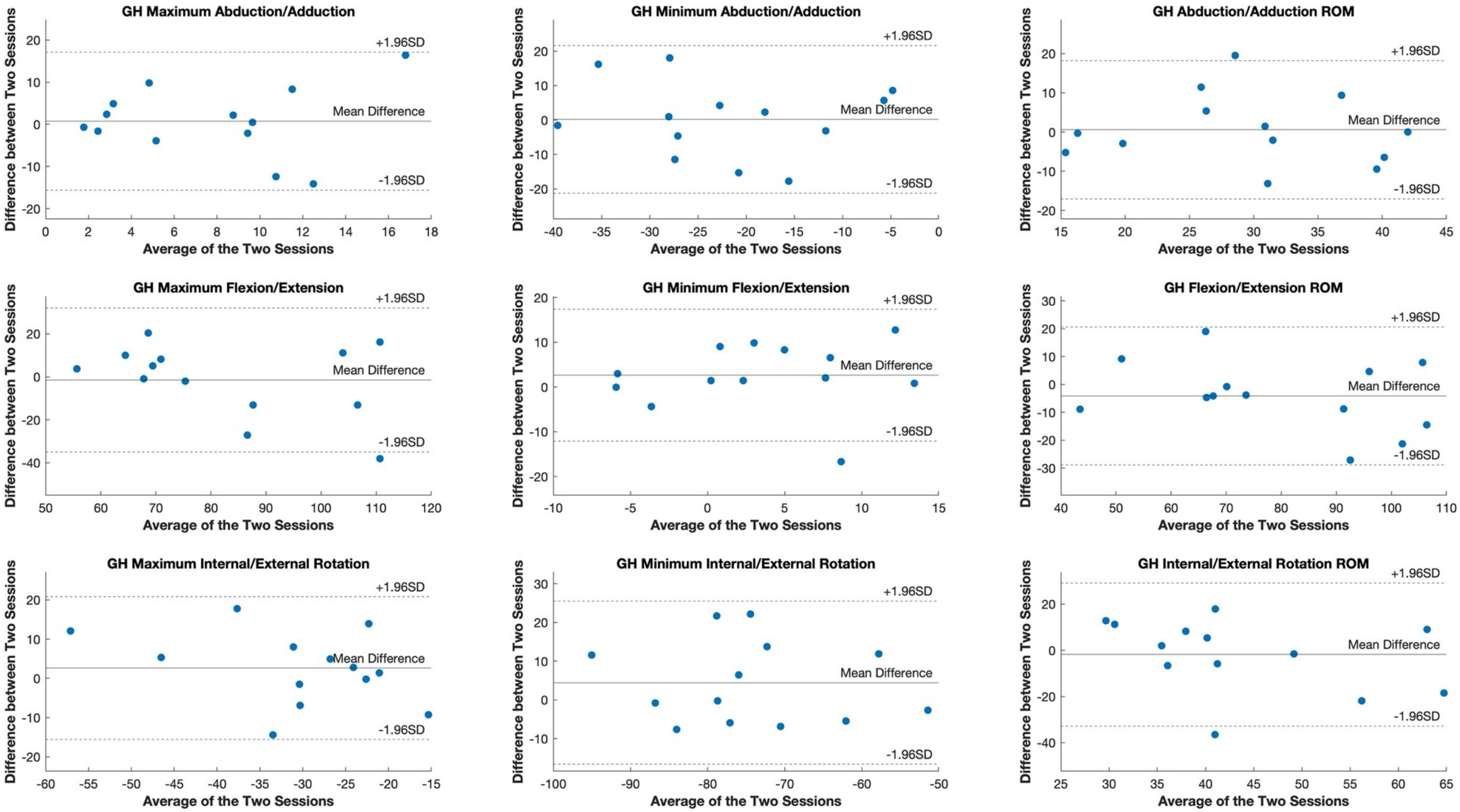
Glenohumeral Kinematics During Tie Apron Task



Glenohumeral Kinematics During Comb through Hair Task



Glenohumeral Kinematics During Flexion Task



Glenohumeral Kinematics During Floor to Shoulder Lift Task