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# From Visual Observation to Quantitative Analysis: Evaluating Shoulder movements using Phase Space Dynamics (PSD)

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# Abstract

This thesis applies Phase Space Dynamics (PSD) to enhance shoulder biomechanics analysis during the FIT-HaNSA test. Analyzing videos of seven healthy individuals from the HULC database, shoulder movements were recorded during a 5-minute task. Kinematic data, extracted using Dartfish® software and processed in Python, were used to calculate eleven PSD features reflecting movement variability and efficiency. The results indicated notable patterns in shoulder movement dynamics, with an alignment between PSD features and key indicators such as fatigue, compensatory movements, and intensity increases. PSD appeared to offer a more detailed and objective analysis compared to traditional methods. The study suggests that PSD could be a valuable tool for enhancing our understanding of shoulder biomechanics, potentially providing useful insights for physiotherapy and rehabilitation.

# Keywords

Phase Space Dynamics, Shoulder Biomechanics, FIT-HaNSA Test, Clinical Application, Rehabilitation, Diagnostic Tools.

# Lay Summary

This thesis explores an innovative method called Phase Space Dynamics (PSD) to enhance the analysis of shoulder movements, particularly during the FIT-HaNSA test, a common assessment of shoulder function involving the repetitive transfer of objects between shelves. Traditional techniques often fail to capture the intricate and complex nature of shoulder movements, but PSD offers a more detailed and accurate analysis. Using videos of seven healthy individuals performing the FIT-HaNSA test, shoulder movements were recorded and analyzed. Kinematic data was extracted using Dartfish® software, and then processed in Python to calculate eleven PSD features reflecting movement variability and efficiency. The analysis showed that PSD could identify subtle differences in shoulder movement patterns, providing important insights into shoulder function. For instance, it was able to detect signs of fatigue, compensatory movements (when the body adjusts to reduce strain), and increased movement intensity more accurately than traditional video analysis. In one part of the study, PSD revealed distinct patterns in shoulder movement dynamics between different participants. For example, Participant 1 exhibited higher variability, complexity, and dispersion in movement patterns, suggesting more flexible or adaptive strategies compared to Participant 3. Another part of the study focused on the concordance between PSD features and key indicators of shoulder performance, such as vocal expressions of fatigue, compensatory movements, and increased movement intensity. The results showed a high level of agreement, highlighting PSD's ability to provide a more comprehensive and objective understanding of shoulder biomechanics. The implications of these findings are significant for clinical practice. By capturing detailed patterns that traditional methods often miss, PSD enhances clinical assessments and can lead to better-targeted rehabilitation methods. This, in turn, can improve the recovery process for individuals with shoulder injuries. Overall, this thesis highlights the potential of PSD as a powerful tool for advancing shoulder biomechanics. By providing a deeper and more precise analysis of shoulder movements during everyday tasks, PSD contributes valuable insights for physiotherapy and rehabilitation, ultimately leading to better diagnosis and treatment strategies for shoulder conditions. This new approach promises to improve the way we understand, diagnose, and treat shoulder-related issues.

# Table of Contents

# List of Tables

**Chapter 2:**

**Chapter 3:**

**Supplementary Materials:**

# List of Figures

# Chapter 1

## 1 Introduction

Musculoskeletal burdens associated with the shoulder joint translate into a significant public health concern. Shoulder disorders (SDs) pose a significant public health concern globally, leading to considerable healthcare utilization and impacting individuals' daily lives. The pain and functional limitations associated with SDs can hinder work productivity, leisure activities, and social interactions, thereby affecting overall quality of life. Furthermore, the economic burden of SDs is substantial, with costs associated with healthcare utilization and sick leave [1].

Understanding the true extent of the global burden of shoulder pain requires a comprehensive assessment of its incidence, prevalence, and associated risk factors. While previous reviews have provided valuable insights, limitations exist, including variations in study populations and methodologies. Recent data from various countries offer a more complete picture of how shoulder disorders affect populations worldwide [2, 3].

Risk factors for SDs are multifaceted, encompassing direct injuries, age-related degeneration, reduced mobility, psychological factors, workplace factors, and comorbid conditions. Identifying these risk factors is crucial for developing prevention and management strategies to reduce the burden of SDs. While pain is a defining symptom, the impact of SDs extends beyond the physical realm. Research suggests that occupational demands, work environments, and psychosocial factors like stress and coping mechanisms can all play a substantial role in disability associated with SDs [4, 5].

Functional assessment tools like the Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) offer valuable insights into individuals' functional limitations and can aid in tailoring rehabilitation programs [6]. Technology such as Dartfish® software enhances this process with advanced video analysis capabilities, particularly in sports performance analysis, contributing to injury prevention, technique improvement, and talent identification. However, these tools natively produce complex time-series data that can be challenging to process. This complexity highlights the potential benefits of integrating Phase Space Dynamics (PSD) techniques, which can simplify and enhance the analysis of such intricate data.

PSD presents a mathematical framework for analyzing complex systems' dynamic behavior, offering insights into various disciplines such as neuroscience, climate science, and finance. Integrating PSD with functional assessment tools like FIT-HaNSA holds promise for improving diagnostic accuracy, assessing treatment efficacy, and unveiling underlying biomechanical abnormalities in shoulder disorders.

This literature review aims to provide a narrative overview of shoulder disorders, including their prevalence, risk factors, assessment tools, technological advancements, and future directions for research and clinical practice. By synthesizing existing knowledge and highlighting emerging trends, this review seeks to contribute to a better understanding of shoulder disorders and inform strategies for their prevention and management.

## 1.1 Risk Factors for Shoulder Disorders

SDs encompass a range of conditions affecting the shoulder joint and surrounding structures, with various factors contributing to their development. Direct injuries, such as trauma from fractures, contusions, ligament tears, and dislocations, significantly increase the risk of SDs [7-10]. Similarly, surgical procedures on the shoulder or intravenous injections can also contribute to their development.

Age-related degeneration is another significant risk factor for SDs. As individuals age, they are more likely to experience degenerative changes in the shoulder joint, such as acromioclavicular and glenohumeral osteophytes (bone spurs), which can contribute to the development of SDs.

Reduced mobility, particularly in the thoracic kyphosis (upper spine) and cervicothoracic spine (upper back) regions, has been identified as a risk factor for SDs [7-10]. Limited mobility in these areas can restrict shoulder movement, predisposing individuals to SDs [7].

Psychological factors, including depression and pain-related behaviors such as fear of movement and pain catastrophizing, can also contribute to the development of shoulder disorders [11]. These factors may lead to avoidance behaviors that perpetuate shoulder pain and disability [4, 5, 12-14].

Workplace factors play a significant role in the development of shoulder disorders. Occupational demands, such as repetitive use of the hands or arms, high workloads, stressful work environments, and lack of control over work tasks, can increase the risk of shoulder disorders. Additionally, long periods between breaks and social isolation in the workplace have been associated with an increased risk of shoulder disorders [4, 15-23].

While the evidence is not conclusive, some studies suggest that gender and anthropometric factors may also influence the risk of shoulder disorders. Women and older workers may be more susceptible to shoulder disorders, although further research is needed to confirm these associations. Anthropometric factors, such as body measurements, may not be significant risk factors for shoulder disorders [4, 15-23].

Comorbid conditions, such as osteoarthritis, stroke, and diabetes mellitus, can occur alongside shoulder disorders, although they are not considered direct causes. It is essential to distinguish these conditions as coexisting rather than causal factors in the development of shoulder disorders. Understanding the various risk factors associated with shoulder disorders is crucial for developing effective prevention and management strategies. By addressing these risk factors through targeted interventions and modifications, healthcare professionals can help individuals reduce their risk of developing shoulder disorders and improve their overall shoulder health [2, 8, 24, 25].

## 1.2 Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA)

The Functional Impairment Test-Hand and Neck/Shoulder/Arm (FIT-HaNSA) has emerged as a promising tool for assessing functional limitations in individuals with shoulder problems. Unlike traditional assessments that often isolate specific movements, the FIT-HaNSA test incorporates a series of tasks designed to mimic everyday activities, offering several advantages for clinicians. Improved Diagnostic Accuracy: The FIT-HaNSA test may aid in diagnosing shoulder conditions by differentiating between healthy individuals and those with limitations. By assessing performance in tasks relevant to daily life, the test can provide a more complete picture of functional capacity compared to isolated movement assessments. Targeted Rehabilitation Planning: The results of the FIT-HaNSA test can help clinicians tailor rehabilitation programs to address specific functional deficits identified during the assessment. This targeted approach allows for a more efficient and effective rehabilitation process, focusing on improving patients' ability to perform the tasks that are most challenging for them. Objective and Subjective Insights: The FIT-HaNSA test offers a unique combination of objective and subjective data [6]. While the test itself provides a quantifiable measure of performance (e.g., time to complete a task), it can also be used in conjunction with patient-reported outcome measures (PROMs) like pain scales or questionnaires about difficulty with daily activities. This combined approach provides a more comprehensive understanding of patients' limitations.

By incorporating quantitative analysis of sub-components, researchers could gain deeper insights into the specific functional deficits identified by the FIT-HaNSA test. This information could then be used to further refine rehabilitation programs and improve patient outcomes. Furthermore, by focusing on real-life tasks and capturing both objective and subjective limitations, the FIT-HaNSA test presents a valuable tool for clinicians managing shoulder dysfunction. Future research can further refine its application and strengthen its role in clinical practice, ultimately leading to improved patient care [6, 26].

## 1.3 Understanding Shoulder Pain: The Importance of Combining Self-Reported Function and Clinical Evaluation

Musculoskeletal shoulder pain ranks among the leading reasons for primary care consultations, trailing only low back and knee pain in prevalence [27]. While the prognosis is variable, with roughly half of patients experiencing persistent symptoms after six months

[28], the impact extends far beyond pain. Functional limitations are a common consequence of shoulder pain, significantly hindering work, leisure activities, and social interactions [29]. Psychological distress and reduced quality of life are often associated concerns, further highlighting the multifaceted burden of this condition [29]. The economic impact is substantial, with studies like one from Sweden reporting a cost per patient exceeding €4,000, with sick leave as the major expense driver [30].

Understanding the true global burden of shoulder pain necessitates a comprehensive assessment of its incidence and prevalence [31]. Previous reviews, such as Luime et al.'s (2001) work, provided valuable insights, but limitations exist [31]. These limitations include potential biases due to variations in study populations, case definitions, and methodological approaches [31]. Furthermore, a growing body of evidence suggests an increase in reported shoulder pain conditions [32]. The substantial increase in research since Luime et al.'s review necessitates an updated evaluation of the global burden of shoulder pain. Recent data from various countries, encompassing both primary care and community settings, offer a more complete picture of how this condition affects populations worldwide [31, 32]. Self-reported data suggests that a significant portion of the population, ranging from 20% to 26% For point-prevalence, experiences shoulder pain at some point [33]. Research has increasingly highlighted the importance of muscle strength in maintaining shoulder health. Studies have demonstrated a positive association between shoulder strength and overall well-being in individuals with shoulder problems [34]. Clinical practice often incorporates self-reported upper extremity function assessments to understand patients' perspectives on their limitations [35, 36]. While valuable for capturing patient experience, these tools are inherently subjective, relying on individual perceptions of functional ability [35, 36]. This subjectivity can potentially lead to discrepancies with objective evaluations performed by healthcare professionals [37].

## 1.4 Dartfish® Software for Performance Analysis

Dartfish® software (Dartfish, https://www.dartfish.com/) is a versatile video analysis solution utilized across various industries, prominently in sports performance analysis. Its key functionalities, applications, and research findings have contributed significantly to performance enhancement.

### Features and Functionalities

Dartfish® offers a range of features and functionalities tailored for comprehensive performance analysis.

Video Capture and Management: Dartfish® allows for the capture of video footage from multiple cameras and formats, facilitating efficient organization and tagging for analysis. Motion Analysis Tools: The software provides tools for in-depth analysis of movement patterns, including slow-motion playback, stroboscopic visualization, and on-screen drawing tools for highlighting key aspects of movement. 3D Analysis: Dartfish® includes an optional 3D analysis module, enabling the reconstruction of movement in three dimensions for a more thorough understanding of complex motions. Synchronization and Integration: It enables the synchronization of video data with external sources such as biomechanical data or physiological measurements, providing a richer context for movement analysis. Collaboration and Feedback Tools: Dartfish® fosters collaboration and feedback by allowing the sharing of annotated videos and reports, facilitating communication between coaches, athletes, and other stakeholders.

## 1.5 Applications in Sports Performance Analysis

Dartfish® has found extensive applications in sports performance analysis, contributing to various aspects of athlete development and performance optimization. Technique Analysis and Improvement: Coaches and athletes utilize Dartfish® to analyze and refine technique across different sports. By comparing movements to established benchmarks or successful athletes' motions, performance gaps can be identified and targeted for improvement. Injury Prevention and Rehabilitation: The software aids in identifying movement patterns that may predispose athletes to injuries and monitoring progress during rehabilitation by tracking changes in movement patterns. Scouting and Talent Identification: Dartfish® assists coaches and scouts in analyzing potential recruits or opponents, providing insights into their strengths, weaknesses, and technical skills. Performance Optimization: By providing objective data on movement patterns, Dartfish® enables coaches to design and tailor training programs to optimize athletes' performance.

Research findings have supported the efficacy of Dartfish®, with studies evaluating hand movements during activities of daily living via grip motion analysis techniques [38] and enhancing the reliability of video gait assessments in children with cerebral palsy [39]. These studies underscore Dartfish's value in diverse applications beyond sports performance analysis, extending to clinical and rehabilitative settings.

Dartfish® software, known for its advanced video analysis capabilities, generates detailed time-series data that can be complex to interpret. Specifically, angles extracted from the lines connecting the elbow to the shoulder and the shoulder to the upper hip mark are used for analysis. This detailed data is crucial for understanding movement patterns but can be challenging to process. As Dartfish® continues to evolve with ongoing research and development, it remains a key tool in performance analysis and outcome improvement across various domains. However, the complexity of the time-series data it produces highlights the potential value of incorporating PSD techniques. PSD can simplify the analysis of such intricate data and provide deeper insights into movement dynamics.

## 1.6 Phase Space Dynamics (PSD)

Phase Space Dynamics (PSD) is a mathematical framework employed to analyze complex systems exhibiting dynamic behavior. It offers a valuable tool for understanding the underlying processes governing a system's evolution over time. Here, we delve into the core concepts of PSD, its applications across various disciplines, and its potential for future advancements in further.

**Theoretical Foundations:**

PSD draws upon the principles of dynamical systems theory. A dynamical system is a system whose state evolves over time according to a set of rules or equations. The concept of a phase space is central to PSD. It represents a multidimensional space where each possible state of the system is depicted by a unique point. The number of dimensions in the phase space corresponds to the number of variables needed to fully describe the system's state. For instance, a system described by position and velocity would require a two-dimensional phase space, with each axis representing one of these variables [40, 41].

### Reconstruction of Phase Space:

Real-world systems typically generate time-series data, a sequence of measurements recorded at regular intervals. PSD utilizes techniques like time delay embedding to reconstruct a system's phase space from these time-series data. Time delay embedding involves creating multiple copies of the time series data, each shifted by a specific time lag. These copies are then stacked together, forming a new space with additional dimensions. By analyzing the trajectories of points within this reconstructed phase space, researchers can gain insights into the system's dynamics.

### Applications of PSD:

PSD has found applications in a wide range of fields due to its ability to analyze complex systems:

- **Neuroscience:** PSD has been used to study brain dynamics, particularly in the context of epilepsy and other neurological disorders. By analyzing electroencephalogram (EEG) signals, researchers can identify characteristic patterns in the phase space that may be indicative of specific brain states [42-44].

- **Climate Science:** PSD is employed to analyze climate data, such as temperature and rainfall patterns. Studying the dynamics within the phase space can help researchers understand and predict long-term climate trends [45, 46].

- **Financial Markets:** Financial time series data like stock prices can be analyzed using PSD to identify patterns and trends, potentially aiding in investment decision-making [47, 48].

- **Engineering:** PSD finds applications in various engineering disciplines, including studying the behavior of vibrating systems and analyzing control systems [49, 50].

**Advantages of PSD:**

- **Quantitative Analysis:** PSD provides a quantitative framework for analyzing complex systems, offering a more objective approach compared to purely qualitative methods.

- **Identification of Hidden Patterns:** By analyzing the phase space, PSD can reveal hidden patterns and relationships within the data that may not be readily apparent in the time series itself.

- **Understanding System Dynamics:** PSD helps to elucidate the underlying dynamics governing a system's behavior, enabling researchers to make predictions about its future states.

**Challenges and Limitations:**

- **Data Requirements:** PSD often requires large amounts of data to accurately reconstruct the phase space. This can be a limitation in situations where data collection is limited.

- **Choice of Time Delay:** The time delay parameter used in time delay embedding can significantly impact the reconstructed phase space. Choosing an appropriate time delay is crucial for obtaining meaningful results.

- **Interpretation of Results:** Interpreting the complex patterns observed in the phase space can be challenging and requires expertise in PSD methods.

**Future Directions:**

PSD research is a continuously evolving field, with ongoing efforts to address existing challenges and explore new applications:

- **Integration with Machine Learning:** Combining PSD with machine learning techniques could lead to automated methods for identifying patterns in the phase space, facilitating data analysis.

- **Application to New Domains:** Researchers are continually exploring the potential of applying PSD to new areas, such as studying social systems and biological processes.
- **Development of User-Friendly Tools:** Developing user-friendly software tools for PSD analysis can broaden its accessibility and facilitate its adoption in various disciplines.

Phase Space Dynamics offers a powerful framework for analyzing complex systems across diverse fields. Its ability to extract meaningful insights from time-series data makes it a valuable tool for researchers and practitioners seeking to understand the underlying dynamics of a system's behavior. As research in this domain continues to progress, we can expect PSD to play an increasingly important role in scientific discovery and technological advancement.

### Leveraging Repetitive Patterns in Movement:

PSD has proven effective in analyzing the repetitive patterns present in EEG signals.

### Understanding Phase Space and its Application:

Within the framework of dynamical systems theory, the concept of a phase space represents a multidimensional space where each possible state of a system is depicted by a unique point. For mechanical systems like the shoulder joint, the phase space typically encompasses various position and momentum variables. Importantly, the phase space can be considered the combined product of both direct space (representing positions) and reciprocal space (representing momenta) [40].

Within the context of movement analysis, PSD transforms time-series data collected during the FIT-HaNSA test (e.g., joint angles, velocities) into a phase space representation. Each axis of this space corresponds to a specific variable relevant to movement, such as position (i.e., of a joint), velocity (i.e., linear or angular), or acceleration [41]. This approach has previously been employed in signal processing and the study of complex systems, offering valuable insights into phenomena like human emotions [42], epileptic seizures [43], and Schizophrenia [44].

### Potential Benefits of Integrating PSD with FIT-HaNSA

The FIT-HaNSA assessment offers a valuable tool for evaluating functional limitations in individuals with shoulder dysfunction. While it provides crucial qualitative insights into patients' ability to perform daily activities, a quantitative analysis of movement patterns could enhance its diagnostic power. This is where PSD emerges as a promising new approach.

Integrating PSD with the FIT-HaNSA test holds several potential benefits:

- **Improved Diagnostic Accuracy:** By quantitatively analyzing movement patterns, PSD has the potential to refine the diagnostic capabilities of the FIT-HaNSA test. Subtle variations in movement dynamics that may not be readily apparent through qualitative observation could be identified using PSD, potentially leading to earlier and more accurate diagnoses of shoulder dysfunction.

- **Objective Assessment of Treatment Efficacy:** PSD can provide an objective measure of changes in movement patterns over time. This quantitative data can be used to evaluate the effectiveness of treatment interventions for shoulder dysfunction, allowing clinicians to track progress and tailor rehabilitation programs more effectively.

- **Unveiling Underlying Biomechanical Abnormalities:** The quantitative analysis offered by PSD may enable researchers to identify specific biomechanical abnormalities associated with different shoulder conditions. This deeper understanding could lead to the development of more targeted treatment strategies.

The potential of PSD to provide a quantitative analysis of movement patterns within the FIT-HaNSA test framework is a promising avenue for advancing the assessment of shoulder function. By incorporating PSD, researchers and clinicians may gain deeper insights into the complex dynamics of shoulder movement and find applations for PSD more broadly with similar systems, ultimately leading to improved diagnosis, treatment optimization, and patient outcomes.

## 1.7 Conclusion

In conclusion, this literature review provides a comprehensive overview of shoulder disorders, including their prevalence, risk factors, assessment tools, technological advancements (i.e., Dartfish®) in measuring shoulder movement, and future research directions. Shoulder disorders pose a significant public health concern globally, impacting individuals' daily lives and imposing substantial economic burdens. Risk factors for shoulder disorders are multifaceted, ranging from direct injuries and age-related degeneration to psychological and workplace factors. Functional assessment tools like FIT-HaNSA offer valuable insights into individuals' functional limitations, aiding in tailored rehabilitation programs. Additionally, technologies such as Dartfish® software provide advanced video analysis capabilities, contributing to injury prevention and performance enhancement.

PSD presents a mathematical framework for analyzing the dynamic behaviour of complex systems, offering insights across various disciplines. Despite its strengths, PSD faces challenges such as data requirements and interpretation complexities. However, ongoing research aims to integrate PSD with machine learning, explore new applications, and develop user-friendly tools, promising advancements in understanding and predicting dynamic systems' behavior.

By synthesizing existing knowledge and highlighting emerging trends, this review contributes to a better understanding of shoulder disorders and informs strategies for prevention, management, and performance enhancement. As research in these areas continues to evolve, interdisciplinary collaborations and technological innovations hold promise for improving outcomes and addressing the global burden of shoulder disorders.

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# Chapter 2 – Manuscript #1

# 2 Enhancing Quasi-Cyclical Movement Analysis: A Phase Space Dynamics Approach for Investigating Shoulder Biomechanics during the FIT-HaNSA Test

## 2.1 Abstract

**Introduction:** This study applies Phase Space Dynamics (PSD), which is a mathematical framework used to analyze complex, multi-dimensional motion patterns, making it particularly suitable for capturing the intricate biomechanics of shoulder movements. By employing PSD, we aim to enhance biomechanical analysis beyond traditional methods, providing a more comprehensive understanding of shoulder function during the FIT-HaNSA test.

**Methods:** The research utilized videos of seven healthy individuals (under 30, three men and four women) from the HULC database. We analyzed shoulder movements performing an eye level reaching subtest from the FIT-HaNSA test, which involves grabbing, transferring, and releasing 1-kg containers between shelves at eye-level for five minutes or until fatigued. We employed PSD to analyze detailed shoulder movements captured by marker-based motion capture. The study focused on 11 PSD features reflecting movement variability, and efficiency, employing Dartfish® software for precision in shoulder angle measurements. Data from Dartfish® were exported into an Excel file for every frame, totaling approximately 1800 frames per video per movement. This data were then imported into Python using the math library. By analyzing the data and applying the PSD features in Python, the extracted data from Dartfish® were used to calculate each feature, yielding the results. This methodical approach facilitated a comprehensive analysis of the biomechanical patterns associated with shoulder movements during the test.

**Results:** The periodic nature of shoulder movements during the FIT-HaNSA test was analyzed through time-series data, capturing the quasi-cyclical pattern essential for the task of shifting containers. Our method effectively demonstrated the oscillating pattern between the initial and final 30 seconds of the test, providing empirical validation for the applicability of the PSD approach to our biomechanical dataset. The study revealed distinct patterns in shoulder movement dynamics between Participant 1 and Participant 3 across 11 PSD features. Participant 1 exhibited higher variability, complexity, and dispersion in movement patterns, suggesting more flexible or adaptive strategies compared to Participant 3.

**Conclusion:** PSD offers a promising avenue for advancing shoulder biomechanics analysis, contributing valuable insights to physiotherapy and rehabilitation.

**Keywords:** Phase Space Dynamics, Shoulder Biomechanics, FIT-HaNSA Test, Marker-Based Motion Capture, Biomechanical Analysis, Movement Efficiency.

## 2.2 Introduction

The dynamic complexity of shoulder mechanics plays a crucial role in diagnosing and rehabilitating musculoskeletal conditions [1, 2]. Functional tests, such as the FIT-HaNSA test [3-5], have been developed to assess the ability to perform repeated functional movements like reaching overhead at work. These tests offer valuable insights into shoulder function and endurance, complementing traditional methodologies in evaluating musculoskeletal health.

Analyzing complex movements in context can be challenging. One effective approach is video-based analysis using Dartfish® software, which provides a robust platform for motion analysis. By offering pertinent feedback tailored to monitoring and assessing patients' progress within clinical environments, Dartfish® software enables a richer and more objective understanding of shoulder function during assessments. This software enables the examination of video inputs sourced from diverse origins and furnishes kinematic outputs to facilitate both spatial and temporal analyses of movement patterns. Dartfish® has been employed in various studies examining healthy and disabled individuals' performance in complex functional tasks such as walking and lifting and hand movements, as well as in athletic activities like speed walking and sprinting, as demonstrated in these studies [6, 7]. Notably, it has demonstrated validity and reliability in assessing both lower body (e.g., hip, knee) [8] and upper limb (e.g., shoulder) movement [9]. Dartfish® excels in identifying various movement parameters, including spatial coordinates (x, y), range of motion, velocity, amplitude, frequency, and movement duration, derived from video inputs associated with task performance.

Analysis of kinematics from video of functional movement is challenging because of the two-dimensional perspective, the fact that functional movements occur in various planes which can obscure landmarks and the fact that clothing or objects that are inherent in functional activity may also limit visualization. Adding to this complexity is that many different criteria and measures can be derived from video analysis and that the capture of these data are often time-consuming. This study introduces an innovative approach by applying phase space dynamics (PSD) to analyze shoulder biomechanics [10, 11]. It focuses on examining the effects of PSD on motion analysis, specifically in the context of the FIT-HaNSA test. Having proven effective in analyzing repetitive patterns found in electroencephalogram (EEG) signals, and considering the inherently repetitive nature of FIT-HaNSA test [12, 13] movements, applying PSD can open a new avenue for investigating the dynamics of shoulder function during this assessment. Within the realm of dynamical systems theory and control theory, the concept of a phase space, also referred to as a state space, delineates a domain where every conceivable state of a dynamic or control system finds representation. Each distinct state maps to a singular point within this space. For mechanical systems, the phase space typically encompasses the entire gamut of position and momentum variables. It emerges as the direct product of both direct space and reciprocal space [10]. PSD translates time-series data into a phase space representation, where each axis delineates a specific variable or derivative of motion, such as position, velocity, or acceleration [11]. PSD, typically employed in signal processing and the study of chaotic systems, offers a unique approach to analyzing complex phenomena such as emotions [14], epileptic seizures [15] and schizophrenia [16]. PSD presents a holistic framework capable of capturing the intricate temporal patterns of shoulder movements, offering enhanced insights into the shoulder complex's functionality throughout the FIT-HaNSA test. PSD offers a comprehensive framework uniquely suited to capturing the intricate temporal patterns of shoulder movements during the FIT-HaNSA test. By doing so, it provides valuable insights into the functionality of the shoulder complex. Unlike conventional methods, PSD bridges the gap by offering enhanced capabilities for analyzing the dynamic and quasi-cyclical nature of shoulder movements. This enables a more nuanced interpretation of biomechanical data, leading to a deeper understanding of shoulder mechanics and facilitating more targeted interventions for musculoskeletal conditions. This research captures detailed shoulder movement data by leveraging the precision of marker-based motion capture technology. This synergy between cutting-edge motion capture and PSD enables an unprecedented level of accuracy in mapping the shoulder's kinematic and kinetic parameters.

This study is dedicated to exploring the impact of Phase Space Dynamics (PSD) on motion analysis, particularly within the context of the FIT-HaNSA test. By exploring the relationship between PSD and marker-based motion capture, we seek to introduce a novel method for examining quasi-cyclical motion patterns. This approach may provide new perspectives on motion analysis and its application to physiotherapy tests like FIT-HaNSA, suggesting that PSD values could offer additional insights with potential implications for diagnostic and rehabilitation practices.

## 2.3 Materials and Methods

*Study Population*

This study utilized video data from seven healthy individuals (mean age= 21.28, three men and four women) performing a reaching subtest from the FIT-HaNSA test at the McFarlane Hand & Upper Limb Center during the summer of 2021. The reaching task involved relocating water bottles across shelves to the rhythm of a metronome for up to five minutes. A dual-camera setup was used to capture the necessary shoulder movements (flexion/extension and abduction/adduction), recording lateral and posterior views. Dartfish® video analysis software was used to measure shoulder angle measurements.

### *Data Acquisition and Analysis Workflow*

The investigation leverages PSD for an in-depth examination of shoulder biomechanics during the FIT-HaNSA test. Marker-based motion analysis, facilitated by Dartfish® software, enabled the accurate tracking of shoulder movement's angles, providing the ability to compute quantitative data on shoulder movement characteristics such as speed and endurance. Participants performed Eye-Down tasks, with markers affixed to crucial anatomical landmarks on the shoulder and a dual-camera setup provided high-resolution videos for analysis. Data from each camera angle were used to assess specific movement types: the lateral view focused on flexion/extension, and the posterior view focused on abduction/adduction. For each frame, the angles of the shoulder to the elbow and the elbow to the hip were calculated. A standard definition camera was positioned to capture the participants' dominant hand side, recording activities performed in the sagittal plane. Concurrently, a high definition camera was placed behind the participants, facing the same direction, to capture activities performed in the coronal plane. The angle of movement was defined as the angle created when two lines extended through the marker. The thoracohumeral angle measured from the sagittal plane represented flexion/extension, while the thoracohumeral angle measured from the coronal plane represented abduction/adduction. These angles were extracted from all frames for analysis. The study's analytical phase involved extracting kinematic data from these videos and segmenting the footage into thirty-second intervals to assess movement patterns and potential fatigue indicators over time using PSD. Data collection was initiated by exporting frame-by-frame data from Dartfish® into an Excel file, resulting in approximately 1,800 frames for each video representing various movements. This dataset was subsequently imported into Python, utilizing the math library for data manipulation and analysis. The analysis involved the application of specific feature equations related to PSD to the extracted Dartfish® data. These equations, which are critical in signal processing, quantify the power present in different frequency components of the movement data. The calculated PSD features provided a detailed understanding of the frequency domain characteristics of the movements. The output of this analysis included key metrics such as dominant frequencies and their respective amplitudes, offering insights into the dynamics of the movements studied.

### PSD Analysis

Traditionally used in signal processing and chaotic systems analysis, the PSD analysis framework was adapted to explore the quasi-cyclical patterns of shoulder movements. This data was then used to feed the PSD equations, enabling a detailed analysis of the shoulder biomechanics during the FIT-HaNSA test. This method involved mapping shoulder angle time series to a two-dimensional space, allowing for examining eleven features. These features were developed because of their ability to shed light on movement variability, efficiency, and fatigue. Through rigorous mathematical analysis and biomechanical expertise, we delve into the calculation, interpretation, and clinical significance of each feature. Eleven features are follow:

1- Summation of consecutive circles area (SCCA) :

The first feature analyzed in the PSD context, known as the Summation of Consecutive Circles Area (SCCA), quantifies amplitude fluctuations in movement over time. This approach calculates the area enclosed by the trajectory path, which involves summing the areas of circles defined between successive points in the PSD plot. Mathematically, SCCA is computed as the cumulative area of circles spanning between consecutive phase space points, as illustrated by Equation 3.1 where $a_i$ (which in our work is shoulder angles) denotes the amplitude at the $i^{th}$ point (which is frames) in the phase space.

Equation 3.1:

$$SCCA = \sum_{i=1}^{m-2} \frac{\pi}{4} \left( \left( a_{i+1} - a_i \right)^2 + \left( a_{i+2} - a_{i+1} \right)^2 \right)$$

2- Summation of successive vector lengths (SSVL):

As the second feature in PSD analysis, the Summation of Successive Vector Lengths (SSVL) offers a measure of the total variability present in the movement signal. The calculation for SSVL is defined mathematically as follows (Equation 3.2).

Equation 3.2:

$$SSVL = \sum_{i=1}^{m-2} \sqrt{\left(a_{i+1} - a_i\right)^2 + \left(a_{i+2} - a_{i+1}\right)^2}$$

3- Summation of the area of the triangles making successive points and coordinate center (TACR)

The third feature, known as the Summation of the Area of Triangles Formed by Successive Points and the Coordinate Center (TACR), is intended to evaluate how motion data is geometrically distributed within the phase space. (TACR)This feature is computed by Equation 3.3.

Equation 3.3:

$$TACR = \frac{1}{2} \sum_{i=1}^{m-2} \left| \det \begin{bmatrix} 0 & a_i & a_{i+1} \\ 0 & a_{i+1} & a_{i+2} \\ 1 & 1 & 1 \end{bmatrix} \right|$$

4- Summation of distances between Heron’s circular (SDHC)

The fourth feature, referred to as the Summation of Distances between Heron’s Circles (SDHC), is a mathematical tool used to analyze the variability in the shape of the PSD. This is achieved by evaluating the distances between points that outline Heron’s circles. The SDHC is computed using Equation 3.4.

Equation 3.4:

$$SDHC = \sum_{i=1}^{m-4} \sqrt{\left(\frac{a_{i+1}+a_{i+2}+a_{i+3}}{3} - \frac{a_i + a_{i+1} + a_{i+2}}{3}\right)^2 + \left(\frac{a_{i+2}+a_{i+3}+a_{i+4}}{3} - \frac{a_{i+1}+a_{i+2}+a_{i+3}}{3}\right)^2}$$

5- Summation of the shortest distance from each point relative to the 45-degree line (SH45)

The fifth feature, called the Summation of the Shortest Distances from Each Point to the 45-Degree Line (SH45), is crucial for examining the scatter width in the PSD. This feature helps reveal directional biases in movement by identifying any consistent deviations from an evenly balanced trajectory. The SH45 is defined mathematically in Equation 3.5.

Equation 3.5:

$$\mathrm{SH45} = \sum_{i=1}^{m-1} \frac{|a_{i+1} - a_i|}{\sqrt{2}}$$

6- Summation of the shortest distance from each point relative to the 135-degree line (SH135)

Feature six, known as the Summation of the Shortest Distances from Each Point to the 135-Degree Line (SH135), is used to evaluate the scatter width relative to an oblique axis within the phase space. The formula for calculating SH135 is given by Equation 3.6.

Equation 3.6:

$$SH135 = \sum_{i=1}^{m-1} \frac{|a_{i+1} + a_i|}{\sqrt{2}}$$

7- Summation of consecutive triangles area (SCTA)

The Summation of Consecutive Triangles Area (SCTA) is intended to capture the intricacy of movement patterns by calculating the areas of consecutive triangles created by the points in PSD. The equation defining SCTA is provided as Equation 3.7.

Equation 3.7:

$$SCTA=\frac{1}{2}\sum_{i=1}^{m-3}\left|\det\begin{bmatrix} a_i & a_{i+1} & a_{i+2} \\ a_{i+1} & a_{i+2} & a_{i+3} \\ 1 & 1 & 1 \end{bmatrix}\right|$$

8- Summation of Heron’s circular areas (SHCA)

Summation of Heron’s circular areas (SHCA) or The Summation of Successive Areas of Irregular Quadrilaterals (SSAIQ), as detailed in Equation 3.8, measures the variability in movement patterns by calculating the areas of irregular quadrilaterals formed between consecutive points in the PSD.

Equation 3.8:

$$SHCA=\sum_{i=1}^{m-3}\pi\left(\frac{\left|\det\begin{bmatrix} a_i & a_{i+1} & a_{i+2} \\ a_{i+1} & a_{i+2} & a_{i+3} \\ 1 & 1 & 1 \end{bmatrix}\right|}{\sqrt{(a_{i+1}-a_i)^2+(a_{i+2}-a_{i+1})^2}+\sqrt{(a_{i+2}-a_i)^2+(a_{i+3}-a_{i+1})^2}+\sqrt{(a_{i+2}-a_{i+1})^2+(a_{i+3}-a_{i+2})^2}}\right)^2$$

9- Summation of distances to coordinate center (SDTC)

The Summation of Distances to the Center (SDTC), represented by Equation 3.9, measures the overall deviation of shoulder movements from a central reference point within the phase space. This metric evaluates the spread of movements, with larger values reflecting greater deviations from the average position and velocity. Such deviations can indicate less controlled or more exploratory movement patterns.

Equation 3.9:

$$SDTC = \sum_{i=1}^{m} \sqrt{a_i{}^2 + a_{i-1}{}^2}$$

10- Summation of the angles between three consecutive points (SABP)

The SABP feature, shown in Equation 3.10, determines the total angular change as the shoulder traverses its range of motion. This metric offers insights into the complexity and smoothness of shoulder movement: abrupt angles may signify sudden directional shifts, potentially indicating compensatory strategies or erratic motion, whereas smoother transitions generally reflect controlled and stable movement patterns.

Equation 3.10:

$$SABP = \sum_{i=1}^{m-3} \frac{(a_{i+1} - a_i)(a_{i+2} - a_{i+1}) + (a_{i+2} - a_{i+1})(a_{i+3} - a_{i+2})}{\sqrt{(a_{i+1} - a_i)^2 + (a_{i+2} - a_{i+1})^2} + \sqrt{(a_{i+2} - a_{i+1})^2 + (a_{i+3} - a_{i+2})^2}}$$

11- Summation of the concessive rectangular area (SCRA)

Equation 3.11 describes the Summation of Consecutive Rectangular Areas (SCRA), which totals the areas of rectangles formed between consecutive points on the PSD plot and fixed lines at 45 and 135 degrees. This calculation effectively combines the variability and directional biases observed in shoulder movements.

Equation 3.11:

$$SCRA = \sum_{i=1}^{m-1} \frac{|a_i + a_{i+1}||a_i - a_{i+1}|}{2}$$

A comprehensive comparison and interpretation of shoulder movements were conducted based on the extracted PSD values and their corresponding concepts and implications. This analysis delved into the individual nuances of each participant's movement patterns, elucidating the unique characteristics and variations observed. By scrutinizing the PSD metrics, including amplitude variations, overall variability, geometric distribution, complexity, and smoothness of movements, a nuanced understanding of shoulder motion dynamics was achieved. This detailed examination facilitated the identification of subtle differences and trends across participants, shedding light on the intricacies of shoulder biomechanics during the test.

Table 1 below provides a brief description of the 11 PSD features used in motion analysis and their relation to shoulder angles.

| PSD Feature | Description |
|---|---|
| **Summation of Consecutive Circles Area (SCCA)** | Quantifies amplitude variations in shoulder angles over time by calculating the area covered by the trajectory motion. (amplitude variations) |
| **Summation of Successive Vector Lengths (SSVL)** | Measures overall variability in shoulder angles by summing the lengths of vectors between consecutive points in phase space. (overall variability) |
| **Summation of the Area of Triangles (TACR)** | Assesses geometric distribution of shoulder angle data by summing the areas of triangles formed by successive points and the coordinate center. (geometric distribution) |
| **Summation of Distances between Heron's Circular (SDHC)** | Evaluates variability of the PSD shape of shoulder angles by examining distances between points forming Heron's circles. (assessing the variability of the PSD shape) |
| **Summation of Shortest Distance to 45-degree Line (SH45)** | Analyzes scatter width of shoulder angles in PSD, providing insight into directional bias by summing the shortest distances from each point to the 45-degree line. (consistent deviation from a balanced trajectory) |
| **Summation of Shortest Distance to 135-degree Line (SH135)** | Assesses scatter width of shoulder angles concerning an oblique axis by summing the shortest distances from each point to the 135-degree line. (assess scatter width concerning an oblique axis) |
| **Summation of Consecutive Triangles Area (SCTA)** | Captures complexity of shoulder angle movement pattern by summing the areas of consecutive triangles formed by PSD points. (capture the complexity) |
| **Summation of Heron's Circular Areas (SHCA)** | Quantifies variability of shoulder angle movement patterns by summing the areas of irregular quadrilaterals formed by consecutive points. (quantify the variability) |
| **Summation of Distances to Coordinate Center (SDTC)** | Measures general deviation of shoulder movements from a central reference point within the phase space, indicating dispersion and control of movements. (quantifies general deviation from a central reference point) |
| **Summation of Angles Between Points (SABP)** | Calculates cumulative angular change in shoulder movements, providing insights into the complexity and smoothness of movements. (complexity and smoothness) |
| **Summation of Consecutive Rectangular Areas (SCRA)** | Aggregates areas of rectangles formed by consecutive points on the PSD plot, capturing variability and directional biases in shoulder angles. (amalgamates the variability and directional biases) |

**Table 1 Brief description of the 11 PSD features used in motion analysis and their relation to shoulder angles.**

For a more detailed analysis, two participants were randomly chosen to compare the result of PSD analysis against each other.

## 2.4 Results

### Quasi-Cyclical Movement Patterns and Feature Efficacy

The periodic nature of shoulder movements during the FIT-HaNSA test is depicted in Appendix 1 for individual level data for all participants. Two participants were randomly selected for a more detailed analysis. Figure 1 compares the raw data of the first and third participants. The x-axis represents the number of frames, totaling approximately 2,400 frames (equivalent to 40 seconds), while the y-axis indicates the shoulder angle (angle between the arm and a line extending from the upper hip mark), derived from Dartfish® software. The quasi-cyclical movement pattern, essential to the task of shifting containers, was captured, demonstrating an oscillating pattern between the initial and final 40 seconds of the test. This pattern underscores the test's repetitive nature and highlights our method's efficacy in capturing these dynamics. Consequently, these findings provided empirical validation for the applicability of the PSD approach to our biomechanical dataset. However, while this approach successfully captured the quasi-cyclical movement pattern observed between the initial and final 40 seconds of the test, it is important to acknowledge its limitations. The analysis provided a basic understanding of the repetitive nature of the task, but detailed and deep insights were not fully extracted, especially considering that interpreting the analysis could be challenging for physicians and experts. This highlights the potential for exploration of PSD in movement analysis, particularly in examining amplitude variations, overall variability, geometric distribution, complexity, quantifying the variability, dispersion, and smoothness of movements. Additionally, the current approach may lack clarity in interpreting performance during the test, presenting challenges for clinicians seeking actionable insights. Thus, PSD analysis can address these limitations and enhance its utility in biomechanical analysis.

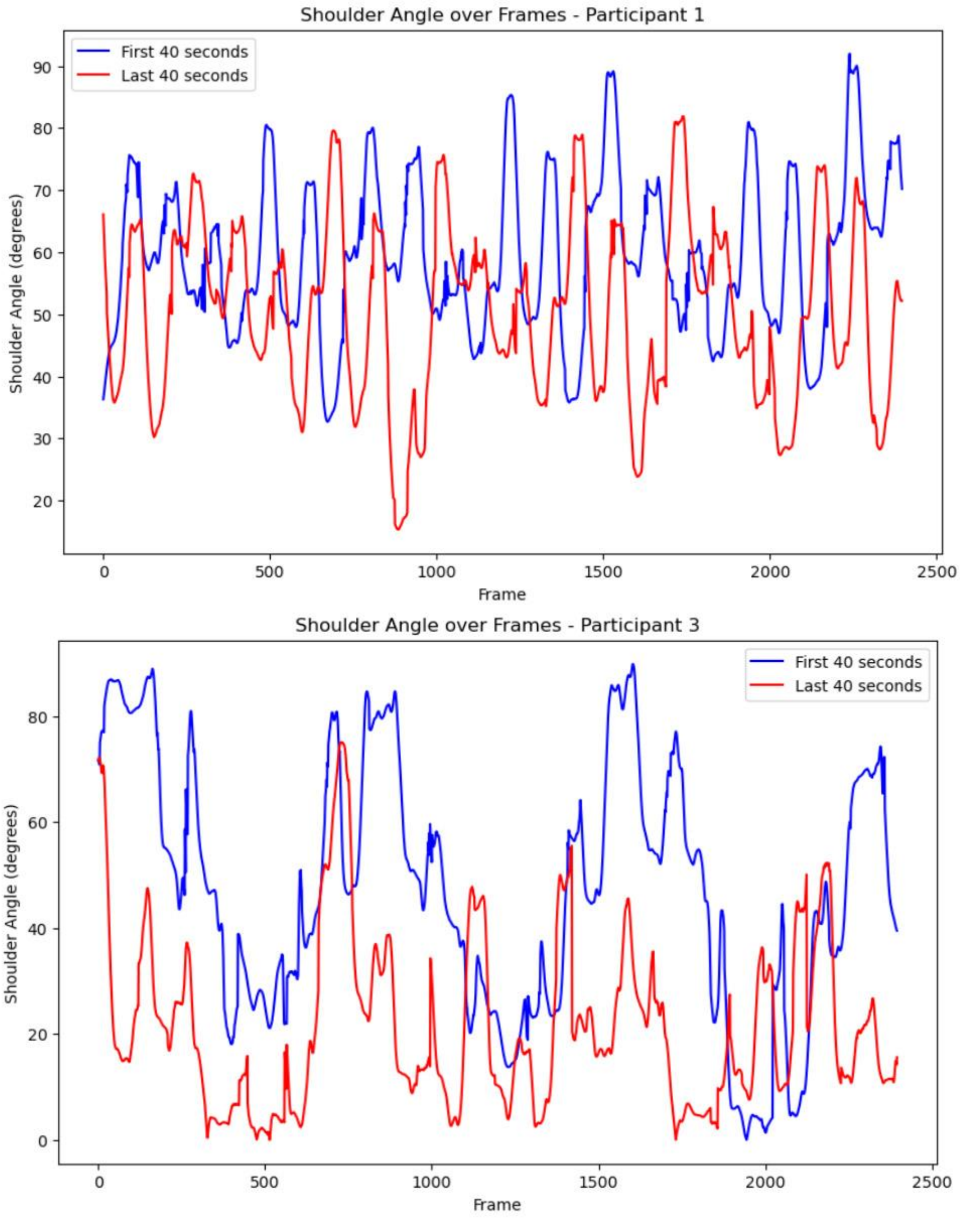

**Figure 1 shows the detailed Analysis of raw data for participant 1 and 3. Blue (first 40 seconds) and red (last 40 seconds) lines illustrate time-series analysis of shoulder movement range during FIT-HaNSA test, highlighting quasi-cyclical motion and variability in early and late test phases. The x-axis shows the number of frames (equivalent to 40 seconds). The y-axis represents the shoulder angle.**

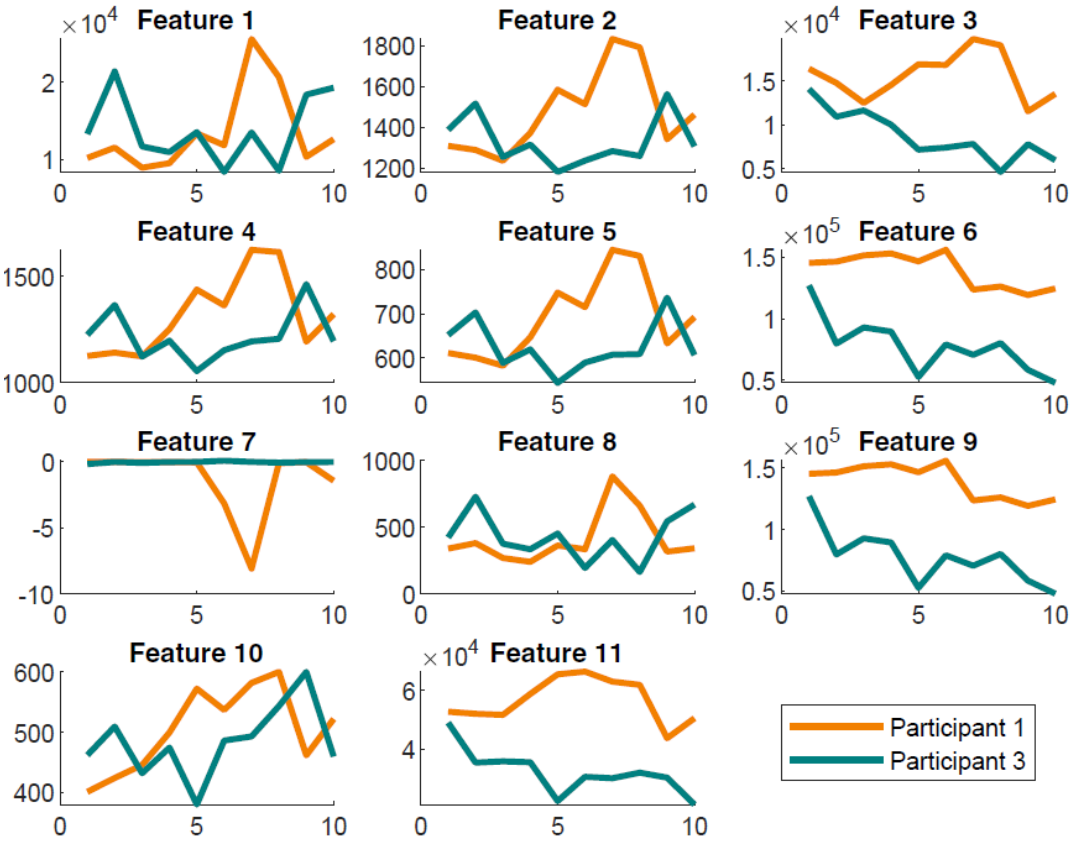

**Figure 2 depicts the values of 11 PSD features for Participant 1 and Participant 3. The x-axis represents the number of intervals, while the y-axis denotes the corresponding feature values. This graphical representation facilitates the comparison and analysis of spectral characteristics between the two participants.**

**Error! Reference source not found.** illustrates the results of PSD analysis conducted on two participants (Participant 1 and Participant 3). The plot displays the variation of feature values across intervals. Notably, Features 1, 2, 3, 4, 5, and 8 exhibit higher values during the latter intervals (6, 7, and 8) for Participant 1. Conversely, there is a notable decrease in Feature 7 during intervals 6 and 7 for Participant 1. The PSD analysis revealed distinct patterns in shoulder movement dynamics between Participant 1 and Participant 3 across the 11 spectral features.

For instance, Participant 1 exhibited an increase in movement amplitude variability during the middle phase of the test, whereas Participant 3 showed higher initial variability, but overall maintained less variability in amplitude compared to Participant 1. Participant 1’s overall movement variability increased during the middle phase and decreased towards the end. Participant 3 maintained a consistent level of shoulder movement variability throughout the test. Geometric distribution analysis indicated that Participant 1’s shoulder movements became more variable during the middle phase. In contrast, Participant 3’s movements showed reduced geometric distribution as the test progressed. PSD shape variability was higher for Participant 1 during the middle phase, while Participant 3 exhibited lower and more stable variability. Directional bias and scatter width analysis showed higher values for Participant 1 during the middle phase. Participant 3 maintained a more balanced trajectory throughout the test. Scatter width around the 135-degree axis was consistently wider for Participant 1. Participant 3 exhibited a decreasing scatter width over time. Feature 7 indicated high variability and complexity in Participant 1’s shoulder movements. Participant 3 maintained stable and low complexity in movement patterns. During intervals 7 and 8, Participant 1 showed higher variability. Participant 3 exhibited moderate variability with less pronounced changes. Movement dispersion was higher for Participant 1. Participant 3’s movements became more focused and less dispersed as the test progressed. Cumulative angular change analysis showed sharper changes in direction for Participant 1 compared to Participant 3. Variability and directional biases differed between participants. Participant 1 exhibited moderate and fluctuating variability and directional biases. Participant 3 showed a reduction in variability and directional biases as the test progressed.

The streamlined Table 2 provides a clear and concise summary of the results and interpretations, highlighting the differences in shoulder movement strategies between the two participants.

Table 2 Summary of PSD Features Analyzed in Shoulder Movements.

| Feature | Result (Report) | Outcome (Interpretation) |
|---|---|---|
| Feature 1 | Participant 1 showed increased variability mid-test; Participant 3 had higher early variability but less overall | Participant 1's higher mid-test variability suggests adaptive strategies; Participant 3's consistency indicates less flexibility |
| Feature 2 | Higher overall variability for Participant 1 in mid-test; consistent variability for Participant 3 | Participant 1's variability indicates adaptation; Participant 3's steadiness suggests controlled movements |
| Feature 3 | More dispersed trajectories for Participant 1 in mid-test; less for Participant 3 | Participant 1's complexity indicates adaptive strategies; Participant 3's focus on consistency. |
| Feature 4 | Greater PSD shape variability for Participant 1 mid-test; stable for Participant 3 | Participant 1 shows diverse trajectories; Participant 3 maintains consistency |
| Feature 5 | Higher directional bias for Participant 1 in mid-test; stable for Participant 3 | Participant 1 suggests exploratory adaptations; Participant 3 indicates controlled movements |
| Feature 6 | Wider scatter for Participant 1; decreasing scatter for Participant 3 | Participant 1 maintains variability; Participant 3 focuses movement patterns |
| Feature 7 | Lower complexity in mid-test for Participant 1; higher for Participant 3 | Participant 1 shows less intricate patterns; Participant 3's complexity indicates adaptability |
| Feature 8 | Higher variability for Participant 1 in later intervals; moderate for Participant 3 | Participant 1 adapts in later stages; Participant 3 maintains consistent movements |
| Feature 9 | Higher movement dispersion for Participant 1; focused movements for Participant 3 | Participant 1's dispersion indicates exploration; Participant 3's control suggests steadiness |
| Feature 10 | Increasing angular changes for Participant 1; smoother for Participant 3 | Participant 1's transitions suggest adjustment; Participant 3's smoother movements indicate delayed fatigue response |
| Feature 11 | Fluctuating variability for Participant 1; consistent reduction for Participant 3 | Participant 1 adapts variably; Participant 3 shows fewer adjustments |

## 2.5 Discussion

This study has demonstrated the potential of PSD to enhance the analysis of shoulder biomechanics during the FIT-HaNSA test, highlighting its capacity to detect clinically relevant changes in fatigue-related movement patterns. By bridging the methodological gap between traditional biomechanical analysis and the detailed investigation required for effective physiotherapeutic intervention, PSD emerges as a valuable tool for advancing clinical practices. Our findings contribute to the body of knowledge surrounding shoulder biomechanics and underscore the importance of innovative methodologies in addressing complex clinical challenges.

The majority of studies employing PSD focus on EEG analysis. Here, we introduce relevant research utilizing PSD and studies with clinical relevance to our current investigation. Zangeneh Soroush et al. [14] presented an innovative approach utilizing phase space dynamics and Poincaré sections for emotion classification. This method introduced a transformation that quantifies phase space, encapsulating signal behavior in a novel state space. The proposed state space and quantifiers effectively described nonlinear signal dynamics, enhancing emotion classification accuracy. In another study by Zangeneh Soroush et al. [17], they employed phase space reconstruction and Poincaré planes to elucidate the dynamics of EEG during emotional states. Utilizing EEG data from a reliable repository, they reconstructed the phase space and introduced a novel transformation to quantify it. The dynamics attributed to this transformed space are regarded as features. They selectively identified the most significant features and classified samples into four distinct groups: high arousal-high valence, low arousal-high valence, high arousal-low valence, and low arousal-low valence. The classification accuracy averaged around 90%. This study provided a pathway for researchers to delve deeper into the analysis and comprehension of chaotic signals and systems using PSD. Sadiq et al. [18] introduced a framework designed to automatically detect alcoholism through the analysis of EEG signals. Initially, the phase space dynamics of EEG signals are investigated to visualize their chaotic nature and complexity. Subsequently, thirty-four graphical features are identified to decipher the chaotic patterns within normal and alcoholic EEG signals. Following this, thirteen feature selection methods are explored in conjunction with eleven machine learning and neural network classifiers to determine the optimal combination for framework efficiency. The experimental findings demonstrate that the proposed approach achieves classification performance, with 99.16% accuracy, 100% sensitivity, and 98.36% specificity utilizing twenty-three selected features. Akbari et al. [16] presented a framework for automated schizophrenia diagnosis, leveraging PSD of EEG signals. It entails plotting the two-dimensional PSD on Cartesian space and extracting fifteen graphical features to assess PSD's chaotic behavior in healthy versus schizophrenic subjects. Using the forward selection algorithm, significant features and optimal channels are identified. Evaluation with eight classifiers, notably the KNN classifier, achieves an average accuracy of 94.80%, sensitivity of 94.30%, and specificity of 95.20%. These results underscore the distinct regularity of PSD shapes in schizophrenia groups, suggesting its potential as a diagnostic biomarker for clinicians.

Contrasting our approach with previous applications of PSD in EEG signal analysis for clinical diagnostics, we see a promising extension of PSD's utility in biomechanical studies. The successful application of PSD in distinguishing emotional states or diagnosing neurological conditions through EEG analysis provides a solid foundation for its adaptation to biomechanical signals. Our study leverages this multidisciplinary approach, showing that the dynamic complexities of shoulder movements can be effectively captured and analyzed through PSD, similar to the intricate patterns observed in EEG signals.

The decline observed in specific PSD features throughout the FIT-HaNSA test aligns with theoretical expectations of fatigue-induced changes in movement efficiency. This movement pattern in the data analysis not only validates the selected features as markers of fatigue but suggests that PSD's might have clinical relevance in the assessment and rehabilitation of shoulder muscle endurance/fatigue. By identifying quantifiable changes in movement patterns that may not be perceptible through visual analysis alone. Further quantifiable indicators of fatigue can be more responsive to detecting changes with interventions than observational or categorical data.

The detailed analysis of shoulder angles for the selected participants provides significant insights into the biomechanics of shoulder movement during the FIT-HaNSA test. Participant 1’s increased amplitude variability in the middle phase suggests a more adaptive or flexible movement strategy. This adaptability could be indicative of attempts to manage fatigue or improve efficiency during repetitive movements. In contrast, Participant 3's lower variability indicates a more consistent but potentially less adaptive movement strategy, which may reflect less flexibility in adjusting to the task demands.

The overall movement variability results indicate that Participant 1's strategy involved higher variability, especially in the middle phase of the test. This could reflect a dynamic approach to managing the repetitive task, possibly by varying movement patterns to cope with fatigue. Participant 3's consistent variability suggests a steadier movement strategy, potentially indicating a focus on maintaining consistent performance without significant adjustments.

The increased geometric distribution of movements observed in Participant 1 suggests more complex and variable movement patterns, possibly as an adaptive strategy to manage the task demands. In contrast, the reduction in geometric distribution for Participant 3 over time indicates a focus on maintaining a specific movement pattern with less variability.

Participant 1's higher PSD shape variability suggests a greater diversity of movement trajectories, reflecting a more adaptive and flexible approach. In contrast, Participant 3's stable variability indicates more consistent movement patterns, which might be indicative of a less adaptive but steadier approach to the task.

The analysis of directional bias and scatter width revealed that Participant 1 exhibited more pronounced deviations from a balanced trajectory, indicating an exploratory or adaptive movement strategy. In contrast, Participant 3 maintained a more balanced trajectory, suggesting a controlled approach to the task.

The consistently wider scatter width around the 135-degree axis for Participant 1 suggests sustained variability and dispersion in movement patterns, indicating an ability to maintain a varied movement strategy despite the repetitive nature of the task. Participant 3's decreasing scatter width suggests a more focused and controlled movement pattern, reflecting a reduction in variability over time.

Feature 7’s high variability and complexity in Participant 1’s movements suggest an adaptive strategy to manage the repetitive task, indicating periods of adjustment or fatigue management. Participant 3’s low complexity indicates a more controlled and repetitive approach, suggesting less need for adjustment.

The higher variability in intervals 7 and 8 for Participant 1 indicates increased complexity in movement patterns during these intervals. Participant 3’s moderate variability suggests a more consistent movement pattern, with less pronounced changes.

Participant 1’s high dispersion of movements indicates more exploratory or less controlled movement patterns, possibly as an adaptive strategy to manage the task. In contrast, Participant 3’s more focused movements suggest a controlled approach, with reduced dispersion over time.

The cumulative angular change analysis showed that Participant 1 exhibited increasing complexity, with sharper changes in direction and less smooth transitions. This might indicate periods of adjustment or compensatory strategies. Participant 3, however, showed smoother transitions earlier, with increasing complexity later, suggesting a delayed response to fatigue or task demands.

Finally, the differences in variability and directional biases between participants highlight individual differences in movement strategies. Participant 1’s moderate and fluctuating variability suggests an adaptive strategy with periods of adjustment. Participant 3’s decreasing variability indicates a steadier approach, with less need for adjustment and directional changes.

In summary, the findings suggest that Participant 1 displayed more variable and complex shoulder movement patterns compared to Participant 3 during the FIT-HaNSA test. These differences in movement strategies have implications for understanding individual biomechanics and designing tailored rehabilitation interventions to improve shoulder function and performance.

The interpretations provided earlier are derived from observations made on two participants. Expanding these interpretations to include a broader cohort of participants and extending them to other motion analysis studies could yield valuable insights for clinicians in decision-making processes and facilitate the discovery of novel insights pertaining to motion-based tests. By examining a larger and more diverse sample of participants, researchers may gain a deeper understanding of the variability and complexity of shoulder movement patterns across different individuals and contexts. Additionally, comparing findings across various motion analysis studies may reveal common patterns or trends that could inform clinical practice and enhance diagnostic and therapeutic approaches for shoulder-related conditions. Therefore, extending the interpretation beyond the current study's scope has the potential to contribute significantly to advancing our understanding of shoulder biomechanics and improving clinical outcomes.

We acknowledge our study's limitations, including the small sample size and the focus on healthy individuals. Investigating a broader array of PSD features across a more diverse population, including those with shoulder impairments, would enhance the robustness and applicability of the findings. Integrating machine learning techniques to analyze the vast datasets generated by PSD could uncover more insights into shoulder biomechanics, facilitating the development of predictive models for diagnosing and managing musculoskeletal disorders. While acknowledging the limitations of our initial exploration, the promising results lay the groundwork for further research. Future studies, enriched by larger, more diverse cohorts and the integration of advanced analytical techniques, hold the potential to profoundly impact the fields of physiotherapy, rehabilitation, and beyond.

Future research should broaden the scope of PSD analysis by incorporating a more comprehensive range of features and a diverse participant pool, including those with shoulder impairments. Integrating machine learning and interdisciplinary approaches could deepen our understanding of shoulder biomechanics and enhance diagnostic and rehabilitation practices. Applying PSD in rehabilitation program design and ergonomic assessments, alongside conducting longitudinal studies, could offer insights into treatment efficacy and musculoskeletal health progression, ultimately contributing to improved therapeutic strategies and workplace ergonomics.

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# Chapter 3 – Manuscript #2

# 3 Enhancing Shoulder Biomechanics Analysis: The Application of Phase Space Dynamics in the FIT-HaNSA Test

## 3.1 Abstract

**Introduction:** This observational study explores the application of Phase Space Dynamics (PSD) to analyze shoulder biomechanics during the FIT-HaNSA test. The primary objectives are to explore how PSD can be used to interpret results from cyclical movement patterns without relying on direct visualization and to identify PSD features that correspond with traditional Dartfish software analysis and visual assessments. Additionally, we aim to identify PSD features that might offer supplementary insights beyond those provided by video observation and traditional analysis methods. This study centers on the potential interpretative value of PSD in understanding shoulder movement patterns.

**Methods:** This observational study explored shoulder biomechanics during the FIT-HaNSA test in seven healthy participants (mean age= 21.28, 3 men and 4 women) from the HULC database. High-resolution video recordings captured participants performing the test, which involved transferring water bottles between shelves for up to five minutes. A dual-camera setup recorded shoulder motions in both flexion/extension and abduction/adduction planes. Three key indicators—vocal expressions of fatigue, compensatory movements, and increased movement intensity—were assessed in 30-second intervals based on both camera views, with the presence or absence of these events evaluated for each participant. Kinematic data were extracted using Dartfish video analysis software, tracking specific anatomical landmarks. PSD analysis was then applied to these kinematic data, calculating eleven distinct features to provide a multidimensional perspective on shoulder movement efficiency and variability. Each 5-minute video was split into 30-second intervals, and PSD features were calculated for each interval. The analysis of PSD features was conducted in Python using appropriate libraries for data manipulation and analysis. To determine the occurrence of an event, intervals in observation indicators and PSD features were binarized. The number of matching zeros and ones were calculated, with a threshold of 0.4 indicating significant changes in PSD values. This threshold was identified as optimal after testing various thresholds from 0.05 to 0.8 in 0.01 steps, selecting the one with the highest number of concordant intervals between PSD features and observation analysis. Detailed results and the comparison of PSD values with observational events are provided in the supplementary materials.

**Results:** By interpreting PSD features based on three key indicators—vocal expressions of fatigue, compensatory movements, and increased movement intensity—we provide a nuanced understanding of shoulder biomechanics In the Flexion/Extension plane, SH45 (94.29%), SCTA (88.57%), and SCRA (92.86%) showed the highest concordance with vocal expressions of fatigue. SCCA (88.57%), SHCA (85.71%), and SABP (82.86%) were most concordant with increased movement intensity. For compensatory movements, SSVL (84.29%), SDHC (84.29%), and SDTC (88.57%) had the highest concordance. In the Abduction/Adduction plane, SH45 (91.43%), SCTA (91.43%), and SCRA (94.29%) aligned best with vocal expressions of fatigue. SCCA (84.29%), SHCA (81.43%), and SABP (81.43%) were most concordant with increased movement intensity. SSVL (87.14%), SDHC (90.00%), and SDTC (88.57%) showed the highest concordance for compensatory movements.

**Conclusion:** By demonstrating how to interpret PSD features, this study provides more detailed and nuanced insights into the dynamic behavior of the shoulder complex based on three indicators. Traditional approaches and video observations often lead to subjective conclusions, whereas PSD allows for objective quantification. PSD features demonstrated notable concordance with key indicators of fatigue, compensatory movements, and increased movement intensity, highlighting its potential for improving diagnostic accuracy and monitoring rehabilitation progress.

**Keywords:** Phase Space Dynamics, Shoulder Biomechanics, FIT-HaNSA Test, Clinical Application, Rehabilitation, Diagnostic Tools.

## 3.2 Introduction

The shoulder joint, characterized by its extensive range of motion and intricate muscular coordination, performs various daily activities and athletic movements. Its complexity makes it susceptible to injuries and disorders that can significantly impact an individual's quality of life (Disselhorst-Klug, 2021) (Lafitte et al., 2022). The shoulder, one of the most complex joint systems in the human body, demands precise analysis tools capable of capturing the nuances of its movement and functionality. The accurate assessment and understanding of shoulder biomechanics and range of motion are pivotal for effectively diagnosing, monitoring, and treating shoulder conditions (Kolk et al., 2017). Traditional methodologies for shoulder assessment, ranging from goniometry to advanced three-dimensional motion capture systems, have provided valuable insights but often need to catch up in capturing the dynamic and cyclical nature of shoulder movements in real-life activities (Scibek & Carcia, 2013). Conventional biomechanical assessments have been integral to understanding shoulder dynamics, employing goniometry, electromyography (EMG), and motion capture systems. While these methodologies offer valuable insights, they often require specialized equipment, are limited by the static nature of the assessments, or need more granularity to capture the full spectrum of shoulder movement in real-life scenarios (Hannah & Scibek, 2015) (Daher et al., 2023).

The Functional Impairment Test - Hand, Neck, and Shoulder Assessment (FIT-HaNSA) test, specifically designed to evaluate the functional performance and endurance of the shoulder girdle (Kumta et al., 2012). This test simulates daily activities, providing a realistic and functional assessment of the shoulder's capabilities (MacDermid et al., 2007).

Recent advancements in technology and analytical methods have prompted a re-evaluation of traditional biomechanical analysis approaches, particularly in dynamic and functional assessment of joint movements. Video-based motion analysis has emerged as a promising tool, providing a less invasive and more accessible means to capture and analyze complex movements (Lempereur et al., 2014). Despite these advancements, the challenge remains to interpret the vast amount of data generated during dynamic assessments accurately and meaningfully. Analyzing complex movements in real-world contexts presents numerous challenges. A highly effective method for addressing these challenges is video-based analysis using Dartfish® software, a powerful tool for detailed motion analysis. Dartfish® software facilitates an objective and comprehensive understanding of shoulder function during clinical assessments by providing detailed feedback that can monitor and evaluate patient progress. The software supports the examination of video inputs from various sources, producing kinematic outputs essential for spatial and temporal movement analysis. Dartfish® has been extensively utilized in research studies focused on both healthy individuals and those with disabilities, investigating their performance in complex functional tasks such as walking, lifting, and hand movements, as well as in athletic activities like speed walking and sprinting (Borel et al., 2011; Holland et al., 2020). Notably, studies have validated the software's accuracy and reliability in assessing movements of both the lower body (e.g., hip, knee) (Norris & Olson, 2011) and upper limbs (e.g., shoulder) (Khadilkar et al., 2014). Dartfish® excels in identifying numerous movement parameters. These include spatial coordinates (x, y), range of motion, velocity, amplitude, frequency, and the duration of movements. These parameters are derived from video inputs and are crucial for evaluating task performance. By enabling detailed motion analysis, Dartfish® provides valuable insights into movement patterns, which are essential for both diagnostic and therapeutic interventions in clinical settings. This capability underscores its significance as a tool for enhancing the assessment and rehabilitation of shoulder function, as well as other movement-related evaluations.

Phase Space Dynamics (PSD) (Guignard, 2005), a concept borrowed from physics and applied mathematics, offers a unique framework for analyzing dynamic systems (Nolte, 2010). It has shown significant promise in fields such as neuroscience, which interprets complex EEG signals (Akbari et al., 2021).

This observational study aims to enhance the understanding of shoulder biomechanics through the application of PSD features during the FIT-HaNSA test. The primary objective is to interpret PSD features based on three key indicators: vocal expressions of fatigue, compensatory movements, and increased movement intensity. By comparing these indicators with video observations and movement patterns, the study seeks to identify specific events that are clear in observations and can be quantitatively analyzed using PSD features. This approach reveals subtle aspects of movement that are often overlooked by traditional methods and subjective assessments. By quantifying these movements, clinicians can achieve greater confidence in their performance assessments. The study sets the stage for future applications in personalized treatment strategies, aiming to enhance patient outcomes in physiotherapy and rehabilitation settings.

## 3.3 Materials and Methods

### Study Design and Participants

This observational study utilized a detailed, participant-specific approach to explore shoulder biomechanics during the FIT-HaNSA test. Seven individuals (mean age= 21.28, 3 men and 4 women), under controlled conditions at the McFarlane Hand & Upper Limb

Center, formed the study cohort. Each participant offered a unique profile to analyze movement patterns, and compensatory strategies during the test.

## Data Collection

The primary data source was the high-resolution video recordings of participants performing the FIT-HaNSA test. The task required participants to transfer water bottles between different shelves in sync with a metronome for a duration of up to five minutes. A dual-camera setup (two cameras) was employed to record from both the side and rear, guaranteeing extensive observation of shoulder motions in abduction/adduction and flexion/extension planes, respectively.

### *Movement Observation and Documentation*

Each participant's performance was meticulously documented, focusing on three key indicators: vocal expressions of fatigue, compensatory movements, and increased movement intensity. Each event was assessed in 30-second intervals, and the presence or absence of these events was evaluated for each participant. The assessment was conducted based on both flexion/extension and abduction/adduction planes. The agreement of an event occurring in both planes was considered as the final decision. This qualitative analysis allowed for a nuanced understanding of each participant's approach to the test, highlighting critical moments of shoulder biomechanics and behavioral adjustments.

### *Indicator Identification*

To comprehensively analyze shoulder movement during the FIT-HaNSA test, we employed a systematic approach to identify key indicators of motion changes. This method was grounded in biomechanical principles and established motion analysis techniques.

**Vocal Expression of Fatigue or Discomfort:** Instances of participants verbally expressing fatigue, discomfort, or difficulty were identified. These expressions provide direct insights into the participant's perceived exertion and motivational state, serving as subjective measures of fatigue. Verbal expressions were documented whenever participants made comments about the test's difficulty or reported pain or numbness.

**Compensatory Movements:** Compensatory movements were identified based on deviations from baseline movement patterns established during the initial phase of the FIT-HaNSA test. These included increased use of the neck for lifting or positioning containers, noticeable leaning sideways, altered shoulder usage with more frequent or pronounced movements, and significant trunk adjustments. Specifically, movements were considered compensatory if there was a marked increase in neck, shoulder, or trunk activity compared to the initial two minutes of the test, as well as frequent and noticeable leaning to one side. These deviations indicated the participants' attempts to manage fatigue or discomfort.

**Increased Movement Intensity:** Increased movement intensity was identified based on thresholds for movement frequency and amplitude, capturing heightened physical effort and the body's response to fatigue. A movement was considered intense if it exceeded the baseline - average of movements per 30-second interval was established during the initial phase (first 30-second interval) of the test - frequency by more than 50% or if the amplitude was 20% greater than the normal range of motion. Both criteria had to be met for an interval to be scored as increased intensity, ensuring significant changes in movement patterns were accurately captured. This combined assessment allowed for a consistent and objective quantification of movement intensity across participants.

**Binary scoring system:** For each identified indicator, a binary scoring system was developed. Each indicator was scored across 10 intervals (30-second segments) for all participants. The presence of an indicator in a given interval was scored as 1, while its absence was scored as 0. Separate sheets were created for each indicator, with rows representing participants and columns representing the intervals. This systematic scoring enabled a detailed comparison of indicators across participants and intervals.

### *Kinematic Analysis*

Dartfish® video analysis software extracted precise kinematic data from the recordings. Specific anatomical landmarks were annotated with markers to facilitate accurate tracking of shoulder movements throughout the FIT-HaNSA test. A standard definition camera was positioned to capture the participants' dominant hand side, recording activities in the sagittal plane. Simultaneously, a high definition camera was placed behind the participants, aligned in the same direction, to capture activities in the coronal plane. The angle of movement was defined as the angle created when two lines extended through the marker. The thoracohumeral angle from the sagittal plane indicated flexion/extension, while the thoracohumeral angle from the coronal plane indicated abduction/adduction.

Participants engaged in Eye-Down tasks, during which markers were attached to key anatomical landmarks on the shoulder. A dual-camera configuration captured high-resolution videos for subsequent analysis. Each camera angle facilitated the examination of distinct movement patterns: the lateral view enabled assessment of flexion/extension, while the posterior view focused on abduction/adduction. The angle formed by the shoulder between the elbow and hip was computed for every frame. These angular measurements were then compiled for analysis. Data collection commenced with the exportation of frame-by-frame data from Dartfish® into an Excel spreadsheet, yielding approximately 1800 frames per video, capturing various movements. Subsequently, this dataset was imported into Python, where the math library facilitated data manipulation and analysis. For extracting PSD features, 5-minute videos were split into 30-second intervals, and PSD features were calculated for each interval, resulting 10 values for each feature in each participant. The analytical process entailed the application of specific equations pertaining to PSD to the Dartfish-derived data. This setup enabled the quantification of movement patterns and the identification of changes or compensatory strategies. Visual assessments were performed by a Master's Physiotherapy student and were subsequently corrected and validated by a Ph.D. physiotherapy expert and a physiotherapy clinician, ensuring the accuracy and reliability of the observational data.

### *Phase Space Dynamics (PSD) Analysis*

PSD Historically employed within the realms of signal processing and the analysis of chaotic systems. It underwent adaptation to delve into the cyclic patterns inherent in shoulder movements. The core of the quantitative evaluation was the application of PSD to the collected kinematic data (shoulder’s angles). Eleven PSD-derived features were calculated for each participant, providing a multidimensional perspective on shoulder movement efficiency and variability. These features offer a comprehensive understanding of shoulder dynamics, encompassing aspects such as amplitude variations, movement variability, geometric distribution, shape irregularity, directional biases (tendencies for the shoulder to move more in one direction than another), and movement complexity. The features include Summation of Consecutive Circles Area (SCCA), Summation of Successive Vector Lengths (SSVL), Summation of the Area of Triangles making Successive Points and Coordinate Center (TACR), Summation of Distances between Heron's Circular (SDHC), Summation of the Shortest Distance from Each Point Relative to the 45-degree Line (SH45), Summation of the Shortest Distance from Each Point Relative to the 135-degree Line (SH135), Summation of Consecutive Triangles Area (SCTA), Summation of Heron’s Circular Areas (SHCA), Summation of Distances to Center (SDTC), Summation of Angles Between Three Consecutive Points (SABP), and Summation of Consecutive Rectangular Areas (SCRA). Table 3 demonstrates these 11 features with their application and concept.

**Table 3: Features and Applications in Shoulder Angle Assessment**

| Feature | Description |
|---|---|
| **SCCA** | Quantifies amplitude variations over time, reflecting the range and intensity of shoulder movements. |
| **SSVL** | Measures overall movement variability, aiding in assessing the stability and consistency of shoulder motion patterns. |
| **TACR** | Evaluates geometric distribution of motion data, offering insights into spatial configuration of shoulder movements. |
| **SDHC** | Assesses PSD shape variability by examining distances between points forming Heron's circles. It indicates irregularities or asymmetries in shoulder movements, which may influence the trajectory and angle of the shoulder joint. |

| | |
|---|---|
| **SH45** | Analyzes scatter width of PSD, indicating directional bias (consistent deviations in movement direction) and trajectory deviations in shoulder movements. |
| **SH135** | Assesses scatter width concerning an oblique axis, providing insights into directional biases within phase space. It provides insights into directional biases and deviations from the optimal movement plane. It affects the orientation and alignment of the shoulder joint, influencing the measured angle. |
| **SCTA** | Captures movement complexity by computing area of consecutive triangles formed by PSD points. It reflects the intricacy and smoothness of shoulder motion. Abrupt changes or irregularities in movement patterns, as indicated by SCTA, may affect the accuracy and consistency of measured shoulder angles. |
| **SHCA** | Quantifies movement pattern variability by computing area of irregular quadrilaterals (SSAIQ) formed by consecutive PSD points. It offers insights into the variability and stability of shoulder movements. Fluctuations in movement patterns, as quantified by SSAIQ, may affect the reliability and interpretation of shoulder angle measurements. |
| **SDTC** | Measures deviation of shoulder movement from central reference point within phase space, indicating dispersion of movements. |
| **SABP** | Calculates cumulative angular change during shoulder motion, providing insights into movement complexity and smoothness. |
| **SCRA** | Aggregates variability and directional biases observed in shoulder movements, offering comprehensive assessment of movement characteristics. |

SCCA: Summation of Consecutive Circles Area, SSVL: Summation of Successive Vector Lengths, TACR: Summation of the Area of Triangles making Successive Points and Coordinate Center, SDHC: Summation of Distances between Heron's Circular, SH45: Summation of the Shortest Distance from Each Point Relative to the 45-degree Line, SH135: Summation of the Shortest Distance from Each Point Relative to the 135-degree Line, SCTA: Summation of Consecutive Triangles Area, SHCA: Summation of

Heron’s Circular Areas , SDTC: Summation of Distances to Center, SABP: Summation of Angles Between Three Consecutive Points, SCRA: Summation of Consecutive Rectangular Areas

## Analytical Approach

The study's analytical framework was designed to ensure a comprehensive understanding of the dynamics of shoulder movements during the FIT-HaNSA test. The research compared video observations of the test with the results of our PSD features to evaluate how these features can enhance motion and movement analysis. This comparison aimed to identify the limitations of video observation and subjective analysis, demonstrating how the PSD approach can address these limitations and provide more detailed insights. The comparison of PSD values and observations was conducted by evaluating the occurrence of events in each interval. For the PSD analysis, a threshold of 0.37 was used to determine the occurrence of an event, meaning changes in PSD values greater than 0.37 were considered indicative of an event happening. This threshold was considered the best threshold, determined through an approach that tested different thresholds from 0.05 to 0.8 in 0.01 steps. The goal was to find the optimum number of overlapped intervals between PSD features and observation analysis, with the highest number of concordances indicating the optimum threshold. This approach aimed to identify the limitations of video observation and subjective analysis, demonstrating how the PSD approach can address these limitations and provide more detailed insights. This dual-analysis approach facilitated a deeper understanding of participant-specific responses and contributed to the broader field of shoulder biomechanics and its clinical applications. Detailed results of the occurrence of events alongside PSD values are provided in the **Supplementary Materials Tables S1-S3**.

## 3.4 Results

Our analysis, grounded in PSD and enhanced by Dartfish® video observation, reveals distinct shoulder movement patterns across seven healthy participants during the FIT-HaNSA test. This section interprets the PSD features based on three key indicators: vocal expressions of fatigue, compensatory movements, and increased movement intensity. By comparing these indicators with observed movements, we provide a nuanced understanding of shoulder biomechanics and the intricate relationships between participant-specific performance, observed events, and calculated PSD features.

### Participant-Specific Performance: PSD Features and Observational Analysis Concordance

The concordance of observations and the three key indicators—vocal expressions of fatigue, compensatory movements, and increased movement intensity—was investigated in detail for each participant. The findings are presented in **Supplementary Material Table S1-S3**. The occurrence of events in observations was recorded as 0 (not happening) and 1 (happening). For PSD features, values in each interval that were higher than 0.37 compared to the previous interval were considered as "change," and these were compared to the observed events.

**Table 4: Concordance of PSD features with observation indicators for each participant in the Flexion/Extension plane. Features with more than 80% similarity in intervals are marked, showing the alignment with vocal expressions of fatigue, compensatory movements, and increased movement intensity.**

| **Participant** | **Indicators** | **features** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCCA | SSVL | TACR | SDHC | SH45 | SH135 | SCTA | SHCA | SDTC | SABP | SCRA |
| **1** | vocal exp. fatigue | | | ✓ | | ✓ | | ✓ | | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **2** | vocal exp. fatigue | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **3** | vocal exp. fatigue | | | | | ✓ | | ✓ | | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | | |
| | Comp. mov. | | ✓ | | | | | | | ✓ | | |
| **4** | vocal exp. fatigue | ✓ | ✓ | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **5** | vocal exp. fatigue | | | | | ✓ | ✓ | ✓ | | ✓ | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | ✓ | | | ✓ | | |
| **6** | vocal exp. fatigue | | | | | ✓ | | ✓ | | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| 7 | vocal exp. fatigue | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |

Intervals in observation indicators and PSD features were binarized. The number of matching zeros and ones were calculated, and the percentages of similar intervals (out of 10 intervals) were documented in **Supplementary Material Table S2** and **Table S3** for Flexion/Extension and Abduction/Adduction, respectively. In

**Table 4**, features with more than 80% similarity were marked for each of the three indicators, showing which features were most concordant with each indicator for each participant in the Flexion/Extension plane. Similarly,

**Table 5** presents the features with more than 80% similarity for the Abduction/Adduction plane.

**Table 5: Concordance of PSD features with observation indicators for each participant in the Flexion/Extension plane. Features with more than 80% similarity in intervals are marked, showing the alignment with vocal expressions of fatigue, compensatory movements, and increased movement intensity.**

| **Participant** | **Indicators** | **features** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCCA | SSVL | TACR | SDHC | SH45 | SH135 | SCTA | SHCA | SDTC | SABP | SCRA |
| **1** | vocal exp. fatigue | | | | | ✓ | | ✓ | | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | ✓ | | ✓ | | |
| **2** | vocal exp. fatigue | | ✓ | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **3** | vocal exp. fatigue | | | ✓ | | ✓ | | ✓ | | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **4** | vocal exp. fatigue | ✓ | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | | ✓ |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **5** | vocal exp. fatigue | | | | ✓ | ✓ | | ✓ | | | ✓ | ✓ |
| | Incr. mov. Int. | | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **6** | vocal exp. fatigue | ✓ | ✓ | | ✓ | ✓ | | ✓ | ✓ | | | ✓ |
| | Incr. mov. Int. | ✓ | | | | | | | ✓ | | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | | | ✓ | | |
| **7** | vocal exp. fatigue | | | | | ✓ | | ✓ | | | ✓ | ✓ |
| | Incr. mov. Int. | ✓ | ✓ | | | | ✓ | | | ✓ | ✓ | |
| | Comp. mov. | | ✓ | | ✓ | | | ✓ | | ✓ | | |

**Table 6: Overall percentage of concordant PSD features with observation indicators across all participants. This table highlights the highest concordance percentages for each PSD feature with three key indicators (vocal expressions of fatigue, compensatory movements, and increased movement intensity) in both Flexion/Extension and Abduction/Adduction planes.**

| **Plane** | **Indicators** | **features** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCCA | SSVL | TACR | SDHC | SH45 | SH135 | SCTA | SHCA | SDTC | SABP | SCRA |
| **Flexion/ Extension** | Vocal Expression of Fatigue | 71.4 | 74.3 | 64.3 | 72.9 | **94.3** | 77.1 | **88.6** | 60.0 | 77.1 | 71.4 | **92.9** |
| | Increased Movement Intensity | **88.6** | 41.4 | 34.3 | 42.9 | 42.9 | 41.4 | 44.3 | **85.7** | 41.4 | **82.9** | 38.6 |
| | Compensatory movement | 57.1 | **84.3** | 44.3 | **84.3** | 52.9 | 60.00 | 48.6 | 50.0 | **88.6** | 54.3 | 51.4 |
| **Abduction/ Adduction** | Vocal Expression of Fatigue | 64.3 | 65.7 | 65.7 | 70.0 | **91.4** | 65.7 | **91.4** | 64.3 | 65.7 | 74.3 | **94.3** |
| | Increased Movement Intensity | **84.3** | 47.1 | 41.4 | 45.7 | 47.1 | 44.3 | 41.4 | **81.4** | 44.3 | **81.4** | 41.4 |
| | Compensatory movement | 55.7 | **87.1** | 51.4 | **90.0** | 54.3 | 54.3 | 60.0 | 55.7 | **88.6** | 51.4 | 57.1 |

**Table 6** presents the overall percentage of concordant PSD features with observation indicators across all participants. In the Flexion/Extension plane, the features showing the highest concordance with the Vocal Expression of Fatigue indicators are SH45 (94.29%),

SCTA (88.57%), and SCRA (92.86%). For Increased Movement Intensity indicators, the most concordant features are SCCA (88.57%), SHCA (85.71%), and SABP (82.86%). The features with the highest concordance for Compensatory Movements are SSVL (84.29%), SDHC (84.29%), and SDTC (88.57%). In the Abduction/Adduction plane, the features showing the highest concordance with the Vocal Expression of Fatigue indicators are SH45 (91.43%), SCTA (91.43%), and SCRA (94.29%). For Increased Movement Intensity indicators, the most concordant features are SCCA (84.29%), SHCA (81.43%), and SABP (81.43%). The features with the highest concordance for Compensatory Movements are SSVL (87.14%), SDHC (90.00%), and SDTC (88.57%).

## 3.5 Discussion

This study's exploration of shoulder biomechanics through PSD analysis during the FIT-HaNSA test underscores the method's potential for clinical applications. PSD analysis has been applied in various fields, including the study of emotions (Soroush et al., 2019; Zangeneh Soroush et al., 2019), epileptic seizures (Bajaj & Pachori, 2013), alcoholic EEG signal recognition (Sadiq et al., 2022) and schizophrenia (Akbari et al., 2021). However, it has not yet been utilized as a tool for analyzing shoulder movement patterns. PSD analysis has proven to be a robust tool for identifying assessing movement efficiency, and understanding compensatory strategies in a clinical context by offering a detailed examination of shoulder dynamics. These findings validate the utility of PSD-derived features in enhancing diagnostic precision and monitoring rehabilitation progress and pave the way for their integration into personalized treatment strategies. The nuanced understanding of shoulder function and dysfunction facilitated by PSD analysis holds promise for advancing physiotherapy and rehabilitation practices, ultimately improving patient care and outcomes. The application of PSD in this study has revealed detailed patterns of shoulder movement that conventional methods may not fully capture. By focusing on three key indicators—vocal expressions of fatigue, compensatory movements, and increased movement intensity—PSD has demonstrated its sensitivity to detecting subtle changes in movement efficiency and variations across participants. The comparison of PSD features with video observations has shown that PSD can provide a more granular view of shoulder mechanics, highlighting specific events and deviations that are often overlooked in traditional assessments.

These findings are crucial for clinicians aiming to understand the biomechanical underpinnings of shoulder disorders. The ability to quantify and analyze detailed movement patterns enables more accurate diagnoses and the development of personalized rehabilitation programs tailored to individual patient needs. By incorporating PSD analysis, clinicians can achieve a higher level of confidence in their performance assessments, ultimately enhancing patient outcomes in physiotherapy and rehabilitation settings. The detailed results, including the concordance of observations with PSD features, underscore the potential of PSD to address the limitations of video observation and subjective analysis. As demonstrated in this study, PSD features such as SH135, SDTC, SABP, and SCRA provide valuable insights into shoulder biomechanics, offering a comprehensive tool for clinical assessment and intervention planning. The congruence between quantitative PSD features and qualitative video observations across all participants reinforces the value of this dual-analysis approach, offering a comprehensive and clinically relevant understanding of shoulder biomechanics. By finding relationships between PSD-derived features with observable changes in movement patterns and participant feedback, this study validates the utility of PSD in biomechanical analysis. The nuanced understanding of movement patterns provides a solid foundation for future research to enhance diagnostic accuracy and the efficacy of rehabilitative strategies for shoulder conditions.

The dynamic nature of PSD analysis (Akbari et al., 2021), exemplified by the ability to track changes in shoulder movement patterns over time, offers a valuable tool for monitoring rehabilitation progress. Perhaps most significantly, the study's findings advocate incorporating PSD analysis into personalized treatment planning. The detailed biomechanical profile generated by PSD can inform more targeted therapeutic exercises, ergonomic adjustments, and preventive strategies, addressing specific vulnerabilities in shoulder mechanics. This personalized approach has the potential to improve outcomes and enhance patient engagement by demonstrating the direct impact of rehabilitation on shoulder function. Integrating PSD into clinical settings requires further research to standardize analysis protocols, validate findings across broader populations, and develop user-friendly tools for routine clinical use. Collaborative efforts between biomechanical researchers, clinicians, and technology developers are essential to translate PSD from a research tool into a practical asset for physiotherapy and rehabilitation.

Additionally, PSD features extracted potential new knowledge about shoulder movement that is not seen in visual assessment. However, the validity of this new knowledge requires further investigation in future studies. Key insights from the PSD analysis suggest that initial stability and adaptation were reflected in features such as SCCA and SSVL, which consistently showed stable and controlled movements during the early phase of the FIT-HaNSA test. This indicates that participants, particularly Participants 1, 2, 4, and 6, effectively engaged with the test requirements, maintaining low variability and consistent movement patterns. As the test progressed, early deviations in features like SDHC and SH45 captured the onset of discomfort and compensatory movements. Participants who reported early discomfort, such as Participants 2, 3, and 5, exhibited noticeable changes in these features, suggesting adjustments in movement patterns to cope with discomfort. Increased movement complexity and variability were captured by features such as SCTA and SHCA, particularly in the later stages of the test. This was evident in Participants 1, 4, and 7, indicating that their movements became more intricate and less predictable as they attempted to offset fatigue through compensatory strategies. Lastly, features such as SABP and SCRA highlighted significant fluctuations and overall variability in movement during the final stages of the test, underscoring participants' efforts to maintain performance. Participants 1, 4, and 6 showed noticeable adjustments, with SABP suggesting changes in shoulder joint angles and SCRA reflecting altered movement paths. These insights are preliminary hypotheses that require comprehensive and rigorous assessment to be validated. The detailed concordance of observations with the three key indicators and PSD features, as shown in Supplementary Materials Table S1-S3, provides a foundation for future research to further explore and validate these findings.

In the both planes, SH45, SCTA, and SCRA showed the highest concordance with vocal expressions of fatigue. SH45, which analyzes the scatter width of PSD, likely indicates directional bias and trajectory deviations, making it sensitive to consistent deviations in movement direction that occur as participants experience fatigue. SCTA, which captures movement complexity, potentially reflects the intricacy and smoothness of shoulder motion, thereby identifying abrupt changes or irregularities that signify fatigue. SCRA aggregates variability and directional biases, providing a comprehensive assessment of movement characteristics that may highlight the overall impact of fatigue on shoulder dynamics. For increased movement intensity, SCCA, SHCA, and SABP were the most concordant features. SCCA quantifies amplitude variations, reflecting the range and intensity of shoulder movements, making it highly responsive to increased physical effort. SHCA quantifies movement pattern variability, offering insights into the stability of shoulder movements, which are likely to fluctuate with increased intensity. SABP calculates cumulative angular change, providing insights into the complexity and smoothness of movement, which tend to increase as participants exert more effort. In the context of compensatory movements, SSVL, SDHC, and SDTC showed the highest concordance. SSVL measures overall movement variability, aiding in assessing the stability and consistency of shoulder motion patterns, which often change with compensatory strategies. SDHC assesses shape variability by examining distances between points forming Heron's circles, indicating irregularities or asymmetries in shoulder movements that arise when compensating for discomfort or fatigue. SDTC measures deviation from a central reference point within phase space, indicating the dispersion of movements, which becomes more pronounced as participants adjust their movements to compensate for fatigue or discomfort.

However, this study has several limitations. The analysis of observations is user-dependent and based on qualitative assessments, which introduces subjectivity. This limitation underscores the need for further investigation through assessments by multiple experts to ensure consistency and reliability. Additionally, the number of participants in this study is limited, which may affect the generalizability of the findings. Future research should involve larger and more diverse populations to validate the results and enhance the robustness of the conclusions. The study likely captures data from a single session or a limited number of sessions, which may not account for day-to-day variability in participants' shoulder movements. Longitudinal studies are needed to understand how shoulder biomechanics evolve over time and under different conditions. Lastly, the FIT-HaNSA test focuses on specific shoulder movements, which may not represent the full range of shoulder activities encountered in daily life, limiting the generalizability of the findings to other types of shoulder movements. Despite these limitations, the study demonstrates the potential of PSD in providing detailed insights into shoulder biomechanics that are not observable through visual assessment alone. However, the validity of these new insights requires further investigation in future studies.

## 3.6 Conclusion

In conclusion, the application of PSD to analyzing shoulder biomechanics during the FIT-HaNSA test offers promising insights into shoulder function and dysfunction. The study suggests that PSD offers a more detailed understanding of shoulder dynamics, potentially capturing subtle patterns that traditional assessments may overlook. In the Flexion/Extension plane, SH45, SCTA, and SCRA showed the highest concordance with vocal expressions of fatigue, while SCCA, SHCA, and SABP aligned with increased movement intensity. For compensatory movements, SSVL, SDHC, and SDTC showed the highest concordance. Similarly, in the Abduction/Adduction plane, SH45, SCTA, and SCRA were most concordant with vocal expressions of fatigue; SCCA, SHCA, and SABP with increased movement intensity; and SSVL, SDHC, and SDTC with compensatory movements. These preliminary findings suggest PSD could enhance diagnostic accuracy, monitor rehabilitation progress, and inform personalized treatment strategies. Further studies are needed to fully validate PSD's clinical potential.

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# Chapter 4

# 4 Discussion

## 4.1 Overview of thesis

The overall goal of this thesis is to advance the analysis of shoulder biomechanics during the Functional Impairment Test – Hand Neck and Shoulder Assessment (FIT-HaNSA) by employing Phase Space Dynamics (PSD). Traditional biomechanical methods often lack the depth needed to capture the complexity of shoulder movements in dynamic, real-world contexts. By integrating PSD, a framework used to analyze multi-dimensional motion patterns, this research aims to provide a more detailed and comprehensive understanding of shoulder function, variability, and efficiency during the FIT-HaNSA test.

**Approach:**

1. **Application of Phase Space Dynamics (PSD)**:
    - PSD was utilized to convert time-series data of shoulder movements into a multi-dimensional phase space, highlighting features such as position, velocity, and acceleration.
    - Eleven specific PSD features were extracted and analyzed to reflect movement variability, efficiency, and complexity.
2. **Comparative Analysis**:
    - Comparative analysis was conducted to identify differences in movement strategies among participants, with a detailed focus on two participants to illustrate the effectiveness of PSD in capturing nuanced shoulder movements.

By integrating PSD with traditional analysis tools, this thesis bridges the gap between conventional methods and the need for detailed, objective quantification of shoulder movement patterns. This approach enhances diagnostic accuracy and provides valuable insights for physiotherapy and rehabilitation, ultimately contributing to improved clinical outcomes.

## 4.2 Lay Summary of Study 1: Enhancing Cyclical Movement Analysis: A Phase Space Dynamics Approach for Investigating Shoulder Biomechanics during the FIT-HaNSA Test

This study aims to improve the analysis of shoulder movements during the FIT-HaNSA test by using a technique called Phase Space Dynamics (PSD). PSD is a method used in different areas to capture repeating patterns, but it hasn't been used to study motion, especially shoulder movements. Traditional methods often miss the detailed and complex nature of how shoulders move. The goal of this study was to see if PSD could better analyze shoulder movements by capturing detailed patterns that conventional methods cannot see. We analyzed the shoulder movements of seven healthy individuals using PSD. Specifically, we compared two participants (Participant 1 and Participant 3) to each other and closely examined their shoulder movement patterns. The results showed that PSD could identify differences in how people move their shoulders, providing important insights into shoulder function and potentially leading to better-targeted rehabilitation methods.

## 4.3 Lay Summary of Study 2: Enhancing Shoulder Biomechanics Analysis: The Application of Phase Space Dynamics in the FIT-HaNSA Test

This study explores whether Phase Space Dynamics (PSD) can give us detailed insights into shoulder movements during the FIT-HaNSA test. The focus was on identifying signs of fatigue (vocal expression), compensatory movements, and increased movement intensity. This study aimed to see if PSD could uncover details about shoulder movements that might be missed or be hard to detect using traditional video analysis. Seven healthy participants took part in the study. The results showed that PSD could accurately detect signs of fatigue, compensatory movements, and increased movement intensity. This means PSD can be a powerful tool for better understanding how shoulders move, improving clinical assessments, and making rehabilitation strategies more effective.

By combining the findings from both studies, this thesis shows how PSD can enhance the analysis of shoulder biomechanics. It offers a deeper and more objective understanding of shoulder function during everyday tasks, leading to better diagnosis and treatment.

## 4.4 Key Findings

**Study 1: Enhancing Cyclical Movement Analysis: A Phase Space Dynamics Approach for Investigating Shoulder Biomechanics during the FIT-HaNSA Test**

1. **Effective Use of PSD**: Phase Space Dynamics (PSD) was successfully applied to analyze shoulder movements, revealing detailed and complex motion patterns that traditional methods did not simply capture.
2. **Identification of Movement Patterns**: PSD identified significant differences in movement variability and complexity among participants, particularly highlighting more adaptive strategies in some individuals.
3. **Quantification of Movement Efficiency**: Eleven PSD features provided a comprehensive analysis of shoulder movement efficiency and variability, offering new insights into the biomechanics of shoulder function during the FIT-HaNSA test.

**Study 2: Enhancing Shoulder Biomechanics Analysis: The Application of Phase Space Dynamics in the FIT-HaNSA Test**

1. **Concordancy with Observational Indicators**: PSD features showed significant concordance with key indicators of fatigue, compensatory movements, and increased movement intensity, providing objective quantification of these aspects.
2. **Enhanced Diagnostic Accuracy**: The study suggested that PSD could potentially detect subtle changes in shoulder biomechanics that might not be clearly visible through traditional video analysis alone.

3. **Application in Clinical Assessments**: PSD appears to be a promising tool for enhancing the understanding of shoulder biomechanics, possibly improving clinical assessments, and informing rehabilitation strategies.

## 4.5 Convergence of Findings

Both studies applied Phase Space Dynamics (PSD) to shoulder biomechanics during the FIT-HaNSA test, though with different focuses. Study 1 initially aimed to determine whether PSD could be applied to shoulder movement analysis. It then extracted insights into shoulder movement patterns and conducted comparisons between participants to analyze differences in shoulder movements. Study 2 went further by focusing on specific indicators such as fatigue, compensatory movements, and increased movement intensity, providing a more straightforward comparison between observational analysis and PSD features. The findings from both studies converged on the potential effectiveness of PSD in capturing complex shoulder movement patterns and providing valuable insights that traditional methods could not offer.

### Complementary Insights

- **Study 1** demonstrated PSD's capability to identify detailed movement patterns and variability among participants, laying the groundwork for understanding how shoulder biomechanics can be objectively quantified. It showed that PSD could analyze motion based on different aspects like variability and compared individual PSD features in two participants.

- **Study 2** built on these insights by showing how PSD features correlate with clinical indicators like fatigue and compensatory movements, thereby extending the practical applications of PSD in clinical settings. It considered PSD based on three specific indicators, providing a clearer and more straightforward comparison.

### Overall Contribution to the Field

The combined findings from these studies enhance the overall understanding of shoulder biomechanics during functional tasks. PSD provides a robust framework for analyzing complex motion patterns, which can improve diagnostic accuracy and inform targeted rehabilitation strategies. This thesis contributes to the field by:

1. **Bridging Methodological Gaps**: It integrates PSD with traditional biomechanical analysis, offering a more comprehensive tool for researchers and clinicians.
2. **Enhancing Clinical Applications**: The objective quantification of shoulder movements through PSD can lead to better diagnosis and treatment of musculoskeletal conditions.
3. **Informing Future Research**: The successful application of PSD in these studies sets a precedent for its use in other areas of biomechanics and movement analysis.

By demonstrating the value of PSD in shoulder biomechanics, this thesis supports the broader adoption of advanced analytical techniques in clinical practice and research, ultimately contributing to improved patient outcomes and a deeper understanding of human movement dynamics.

## 4.6 Similar studies

The majority of studies utilizing (PSD primarily focus on electroencephalogram (EEG) analysis. This section reviews relevant research employing PSD, with particular attention to studies of clinical significance related to our investigation. A study introduced a novel approach utilizing PSD and Poincaré sections for emotion classification. This method included a transformation that quantifies phase space, capturing signal behavior in a new state space. The resulting state space and quantifiers effectively described the nonlinear dynamics of signals, thereby improving the accuracy of emotion classification. In a subsequent study, they employed phase space reconstruction and Poincaré planes to explore EEG dynamics during emotional states. Using EEG data from a reliable repository, they reconstructed the phase space and introduced a new transformation to quantify it. The dynamics of this transformed space were used as features. By selecting the most significant features, they classified samples into four distinct emotional states: high arousal-high valence, low arousal-high valence, high arousal-low valence, and low arousal-low valence. The classification accuracy achieved was around 90%, providing a pathway for researchers to further analyze and understand chaotic signals and systems using PSD. In another study presented a framework for the automatic detection of alcoholism through the analysis of EEG signals. Initially, they examined the phase space dynamics of EEG signals to visualize their chaotic nature and complexity. They identified thirty-four graphical features to decipher the chaotic patterns within normal and alcoholic EEG signals. Subsequently, they explored thirteen feature selection methods combined with eleven machine learning and neural network classifiers to determine the optimal combination for the framework. Their experimental findings demonstrated a classification accuracy of 99.16%, sensitivity of 100%, and specificity of 98.36% using twenty-three selected features. A study developed a framework for automated schizophrenia diagnosis by leveraging PSD of EEG signals. Their method involved plotting the two-dimensional PSD on Cartesian space and extracting fifteen graphical features to assess PSD's chaotic behavior in healthy versus schizophrenic subjects. Using the forward selection algorithm, they identified significant features and optimal channels. Evaluation with eight classifiers, notably the KNN classifier, achieved an average accuracy of 94.80%, sensitivity of 94.30%, and specificity of 95.20%. These results highlighted the distinct regularity of PSD shapes in schizophrenia groups, suggesting its potential as a diagnostic biomarker for clinicians. Overall, these studies underscore the utility of PSD in analyzing EEG signals for various clinical applications, demonstrating significant improvements in classification accuracy and offering promising avenues for further research in the field.

## 4.7 Limitations

### Limitations of Study 1: Enhancing Cyclical Movement Analysis: A Phase Space Dynamics Approach for Investigating Shoulder Biomechanics during the FIT-HaNSA Test

1. **Sample Size and Diversity**: The study involved only seven healthy individuals, which limits the generalizability of the findings. The sample size is small, and the participants were all young and healthy, which does not represent the broader population, including those with shoulder impairments.

2. **Single Functional Task**: The study focused solely on the FIT-HaNSA test. Different tasks or a broader range of activities could provide more comprehensive insights into shoulder biomechanics.
3. **Technology and Software Limitations**: The use of Dartfish software for video analysis, while advanced, may introduce errors in marker placement and tracking, potentially affecting the accuracy of the kinematic data.
4. **Short Duration of Analysis**: The analysis was limited to the duration of the FIT-HaNSA test, which may not capture long-term patterns or fatigue effects that develop over extended periods.

**Impact on Results**: These limitations could lead to biased results, where the identified movement patterns may not be entirely representative of the general population or different contexts. The small sample size and homogeneous group might limit the applicability of the findings to diverse populations, and technological limitations could introduce measurement inaccuracies.

### Limitations of Study 2: Enhancing Shoulder Biomechanics Analysis: The Application of Phase Space Dynamics in the FIT-HaNSA Test

1. **User-Dependent Observations**: The analysis depended heavily on user observations and qualitative assessments, introducing a level of subjectivity. This highlights the need for evaluations by multiple experts to ensure reliability.
2. **Limited Participant Pool**: The study involved a small number of participants, which may limit the generalizability of the findings. Future studies should include larger and more diverse populations to confirm the results and strengthen the conclusions.
3. **Single Session Data**: Data were collected from a single session which might not capture day-to-day variations in shoulder movements. Longitudinal studies are necessary to understand how shoulder biomechanics change over time and under different conditions.

4. **Specific Movement Focus**: The FIT-HaNSA test targets specific shoulder movements, which may limit the applicability of its findings to other shoulder activities encountered in daily life or clinical settings.
5. **Lack of Clinical Population Validation**: The study did not include participants with shoulder impairments, limiting the validation of PSD as a diagnostic tool for clinical populations.

**Impact on Results**: The reliance on subjective assessments and qualitative indicators introduces potential observer bias, affecting the reliability of the findings. The small sample size and controlled study environment limit the external validity, making it difficult to generalize the results to broader, real-world conditions. Additionally, without including impaired populations, the clinical relevance and applicability of PSD as a diagnostic tool remain uncertain. Despite these limitations, the study highlights the potential of PSD in providing detailed insights into shoulder biomechanics that are not easily observable through traditional methods. Further research with larger, more diverse populations and longitudinal data is needed to validate and expand these findings.

### Overall Thesis Limitations

1. **Sample Size and Homogeneity**: The studies included a small number of young, healthy participants, limiting the generalizability of the findings to broader and more diverse populations.

2. **Methodological Constraints**: The reliance on video analysis and specific software (Dartfish) introduces potential measurement errors and biases. The subjective nature of some observational indicators adds another layer of potential bias.

3. **Scope of Analysis**: The focus on a single functional test (FIT-HaNSA) and short analysis duration limits the understanding of shoulder biomechanics across different tasks and over longer periods.

4. **Lack of Clinical Validation**: The studies did not include participants with shoulder impairments, which is crucial for validating PSD as a clinical tool.

**Impact on Results**: These limitations may lead to biased or incomplete findings, reducing the applicability and reliability of the results. The sample size and methodological constraints could introduce errors and limit the generalization of the findings. The narrow scope and lack of clinical validation mean the results might not fully address the overarching research question of enhancing shoulder biomechanics analysis across various contexts and populations. Future studies should address these limitations by including a broader range of participants, validating findings with impaired populations, and exploring additional functional tasks and longer analysis durations. Furthermore, incorporating more objective measures, such as electromyography (EMG) for muscle activity, could improve data accuracy. This would enhance the robustness and applicability of PSD in clinical settings and contribute to a more comprehensive understanding of shoulder biomechanics.

### Biomechanical Analysis

This thesis integrates PSD with traditional video analysis, introducing a novel and comprehensive method for assessing shoulder biomechanics. PSD enables the capture of intricate motion patterns and variability that conventional techniques may overlook. The objective quantification provided by PSD reduces reliance on subjective assessments and enhances the precision of biomechanical analysis.

### Clinical Applications

The findings indicate that PSD may serve as a powerful diagnostic tool, detecting subtle changes in shoulder biomechanics such as fatigue and compensatory movements. This capability may lead to earlier and more accurate diagnoses of shoulder impairments. Additionally, the detailed insights into individual movement patterns might inform personalized rehabilitation programs, allowing clinicians to monitor progress and adjust interventions with precise biomechanical feedback.

### Research and Educational Impact

This research establishes a foundation for future studies to explore PSD in other joints and movements, promoting interdisciplinary approaches that blend biomechanics with signal processing and chaotic systems analysis. The methodologies and findings can also be integrated into educational programs for physiotherapists and biomechanists, enhancing their understanding of advanced analytical techniques.

### Technological Integration

The successful application of PSD in this thesis can drive the development of advanced software tools for routine use in clinical and research settings, making sophisticated biomechanical analysis more accessible to practitioners.

### Specific Contributions to the Field

1. **Validation of PSD in Biomechanics**: Demonstrates the effectiveness of PSD in capturing detailed and clinically relevant motion patterns in shoulder movements.
2. **Comprehensive Movement Analysis**: Identifies specific PSD features that correlate with movement efficiency and variability, providing a robust framework for biomechanical assessment.
3. **Novel Insights into Shoulder Function**: Offers new understanding of individual variations in shoulder movements, informing personalized rehabilitation strategies.

### Practice Implications

The integration of PSD into shoulder biomechanics analysis presents several practical changes for clinical practice and the training of healthcare professionals:

1. **Enhanced Diagnostic Tools**: PSD can be incorporated into diagnostic procedures to provide more detailed and objective assessments of shoulder function. This can lead to earlier detection of impairments and more precise monitoring of patient progress.
2. **Personalized Rehabilitation Programs**: The detailed insights provided by PSD can help clinicians design and tailor rehabilitation programs specific to individual patient needs. By understanding the unique movement patterns and variability of each patient, more effective and personalized treatment plans can be developed.
3. **Advanced Monitoring Techniques**: PSD enables continuous and detailed monitoring of shoulder movements, allowing for real-time adjustments to treatment

plans based on precise biomechanical feedback. This can improve the overall effectiveness of rehabilitation interventions.

### Training of Professionals

1. **Incorporation into Educational Curricula**: The methodologies and findings from this research can be integrated into the educational programs of physiotherapists, biomechanists, and other healthcare professionals. Training programs can include modules on the application of advanced motion tracking and PSD in biomechanics, enhancing the skill set of new professionals entering the field.

2. **Professional Development**: Existing practitioners can benefit from workshops and continuing education courses focused on the use of PSD in clinical settings. This can help bridge the gap between current practice patterns and the advanced analytical techniques demonstrated in this thesis.

### Gaps Between Evidence and Practice Patterns

1. **Integration with Existing Systems**: There may be challenges in integrating PSD with existing diagnostic and rehabilitation practices. Overcoming these barriers requires collaboration between researchers, clinicians, and technology developers to create seamless integration solutions.

2. **Clinical Validation and Standardization**: While the research demonstrates the potential of PSD, further clinical validation with larger and more diverse populations is necessary. Standardizing the use of PSD in various clinical settings will be crucial for its widespread adoption.

Advocating for increased funding from government agencies and health organizations will support further research and development. Additionally, establishing national databases to collect and analyze PSD data will aid in continuous improvement and evidence-based policymaking. Encouraging interdisciplinary collaboration and working towards international standards will facilitate global adoption and consistency.

## 4.8 Future Research Directions

Future research should focus on conducting large-scale clinical trials to validate PSD's effectiveness across diverse populations. Extending PSD application to other joints and movements, and integrating machine learning models to enhance data interpretation will be beneficial. Longitudinal studies on the impact of PSD-guided rehabilitation programs on patient outcomes are also crucial. Interdisciplinary collaboration, including diverse participant samples, and conducting studies in real-world clinical settings will ensure practical applicability. Continuous feedback from clinicians and patients will help refine PSD applications to meet user needs. These steps and research directions will advance the field of shoulder biomechanics and improve the effectiveness of diagnostic and rehabilitation strategies.

### Priority Next Studies

To advance the field of shoulder biomechanics and the application of PSD, the following studies should be prioritized:

- **Large-Scale Clinical Trials**: Conduct extensive clinical trials to validate the effectiveness of PSD in diagnosing and treating shoulder impairments across a broader and more varied population, including individuals with different shoulder conditions.

- **Application of PSD to Other Joints**: Explore the use of PSD in analyzing the biomechanics of other joints, such as the knee and hip, to determine its generalizability and potential broader applications in movement analysis.

- **Integration with Real-Time Monitoring**: Develop real-time monitoring systems that incorporate PSD analysis, allowing for immediate feedback and adjustments during rehabilitation sessions.

- **Longitudinal Impact Studies**: Investigate the long-term effects of PSD-guided rehabilitation programs on patient outcomes to assess sustained improvements in shoulder function and overall quality of life.

- **Interdisciplinary Collaborative Research**: Encourage collaborative research efforts that bring together biomechanists, physiotherapists, software developers, and clinicians to address practical challenges and innovate new solutions for biomechanical analysis.

By addressing these methodological implications, challenges, and priority areas for future research, the field of shoulder biomechanics can continue to evolve, providing more effective tools and techniques for clinical practice and improving patient outcomes.

# Enhancing Shoulder Biomechanics Analysis through Phase Space Dynamics during the FIT-HaNSA Test

We wanted to know : How can Phase Space Dynamics (PSD) improve the analysis of shoulder biomechanics during the FIT-HaNSA test compared to traditional methods?

## What is the problem?

Traditional methods for analyzing shoulder biomechanics often fail to capture the detailed and complex nature of shoulder movements, especially in dynamic and functional contexts. This gap in analysis limits our understanding of shoulder function and impedes the development of effective rehabilitation strategies. By using PSD, which can provide a multi-dimensional perspective on movement patterns, we aim to overcome these limitations and offer more precise diagnostic and therapeutic tools.

## How did the team study the problem?

The research involved analyzing shoulder movements of seven healthy participants performing the FIT-HaNSA test, which involves transferring water bottles between shelves. High-resolution video recordings captured the shoulder motions, which were then analyzed using Dartfish video analysis software to extract kinematic data. PSD was applied to these data to calculate eleven distinct features, providing a detailed and nuanced understanding of shoulder movement efficiency and variability. The study also included observational indicators such as vocal expressions of fatigue, compensatory movements, and increased movement intensity, which were correlated with PSD features.

## What did the team find?

The study found that PSD could effectively capture detailed shoulder movement patterns and variability, which traditional methods might miss. PSD features showed significant concordance with indicators of fatigue, compensatory movements, and increased movement intensity. These findings suggest that PSD can provide a more comprehensive and objective analysis of shoulder biomechanics, offering new insights that can enhance diagnostic accuracy and rehabilitation strategies.

## How can this research be used?

The results of this research can be used to improve clinical assessments and rehabilitation programs for shoulder impairments. By integrating PSD into routine diagnostic procedures, clinicians can gain more detailed insights into shoulder function, leading to more personalized and effective treatment plans. This approach can also enhance the monitoring of rehabilitation progress, allowing for real-time adjustments based on precise biomechanical feedback.

## Cautions

This study has limitations, including a small sample size of healthy participants, which may limit the generalizability of the findings to broader and more diverse populations. The reliance on subjective observational indicators could introduce bias, and the controlled conditions of the study may not fully replicate real-world scenarios. Further research is needed to validate these findings in larger and more varied populations, including individuals with shoulder impairments. Additionally, the development of more user-friendly PSD tools and automated analysis systems will be crucial for broader implementation.

# Appendices

Details of observations and PSD features for each participant during the FIT-HaNSA test. The Tables S1-S3 includes the number of presence or absence of events (vocal expressions of fatigue, compensatory movements, and increased movement intensity) assessed in 30-second intervals, alongside corresponding PSD feature values.

**Table S1: presence (1) or absence (0) of events (vocal expressions of fatigue, compensatory movements, and increased movement intensity) assessed in 30-second intervals in 7 participants.**

| **Participant** | | **Intervals** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| **1** | Vocal expressions of fatigue | **0** | **1** | **0** | **0** | **1** | **0** | **0** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **0** | **0** | **1** | **1** | **0** | **1** | **1** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **0** | **0** | **1** | **1** | **1** | **1** | **1** | **1** |
| **2** | Vocal expressions of fatigue | **0** | **0** | **1** | **0** | **0** | **1** | **0** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **0** | **0** | **1** | **1** | **0** | **1** | **1** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **0** | **0** | **1** | **1** | **1** | **1** | **1** | **1** |
| **3** | Vocal expressions of fatigue | **1** | **0** | **0** | **1** | **0** | **0** | **0** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **1** | **1** | **1** | **1** | **0** | **1** | **1** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **0** | **1** | **1** | **1** | **1** | **1** | **1** | **1** |
| **4** | Vocal expressions of fatigue | **0** | **0** | **0** | **0** | **1** | **0** | **0** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **0** | **1** | **0** | **1** | **0** | **1** | **0** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **0** | **0** | **1** | **0** | **1** | **0** | **1** | **1** |
| **5** | Vocal expressions of fatigue | **0** | **0** | **1** | **0** | **0** | **0** | **0** | **1** | **0** | **0** |
| | Compensatory movements | **0** | **0** | **1** | **0** | **1** | **0** | **1** | **1** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **1** | **0** | **1** | **0** | **1** | **1** | **1** | **1** |
| **6** | Vocal expressions of fatigue | **0** | **0** | **1** | **0** | **0** | **0** | **1** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **0** | **1** | **0** | **1** | **1** | **1** | **0** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **1** | **0** | **1** | **1** | **1** | **1** | **1** | **1** |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | Vocal expressions of fatigue | **1** | **0** | **0** | **0** | **0** | **0** | **1** | **0** | **0** | **0** |
| | Compensatory movements | **0** | **1** | **0** | **0** | **1** | **1** | **1** | **0** | **0** | **0** |
| | Increased movement intensity | **0** | **0** | **0** | **0** | **1** | **1** | **1** | **1** | **1** | **1** |

**Table S7: percentages of intervals comparing observations and 11 PSD features for each indicator (vocal expressions of fatigue, compensatory movements, and increased movement intensity) for each participant in the Flexion/Extension plane. The values are based on percentage of similar intervals between 10 intervals (%).**

| **Participant** | **Indicators** | **features** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCCA | SSVL | TACR | SDHC | SH45 | SH135 | SCTA | SHCA | SDTC | SABP | SCRA |
| **1** | vocal exp. fatigue | 70 | 70 | 80 | 60 | 100 | 70 | 90 | 60 | 70 | 60 | 80 |
| | Incr. mov. Int. | 100 | 50 | 40 | 60 | 60 | 50 | 60 | 90 | 50 | 80 | 50 |
| | Comp. mov. | 70 | 90 | 40 | 90 | 40 | 70 | 40 | 60 | 90 | 40 | 50 |
| **2** | vocal exp. fatigue | 70 | 70 | 70 | 70 | 100 | 90 | 80 | 60 | 90 | 70 | 100 |
| | Incr. mov. Int. | 90 | 50 | 50 | 50 | 50 | 50 | 40 | 90 | 50 | 90 | 50 |
| | Comp. mov. | 50 | 90 | 50 | 80 | 50 | 50 | 40 | 50 | 100 | 50 | 50 |
| **3** | vocal exp. fatigue | 70 | 70 | 70 | 70 | 90 | 70 | 90 | 70 | 70 | 60 | 90 |
| | Incr. mov. Int. | 80 | 20 | 20 | 20 | 20 | 20 | 60 | 80 | 20 | 70 | 20 |
| | Comp. mov. | 50 | 80 | 50 | 70 | 50 | 50 | 30 | 50 | 80 | 60 | 50 |
| **4** | vocal exp. fatigue | 80 | 80 | 50 | 80 | 90 | 90 | 90 | 50 | 90 | 80 | 100 |
| | Incr. mov. Int. | 90 | 50 | 40 | 50 | 50 | 60 | 40 | 80 | 60 | 80 | 40 |
| | Comp. mov. | 60 | 80 | 50 | 80 | 60 | 70 | 50 | 50 | 90 | 60 | 50 |
| **5** | vocal exp. fatigue | 70 | 70 | 70 | 70 | 90 | 100 | 80 | 70 | 100 | 70 | 100 |
| | Incr. mov. Int. | 90 | 30 | 30 | 30 | 30 | 60 | 60 | 90 | 60 | 90 | 30 |
| | Comp. mov. | 50 | 80 | 50 | 90 | 50 | 80 | 60 | 50 | 80 | 50 | 50 |
| **6** | vocal exp. fatigue | 70 | 70 | 60 | 70 | 100 | 60 | 100 | 60 | 60 | 70 | 90 |
| | Incr. mov. Int. | 80 | 40 | 30 | 40 | 40 | 10 | 30 | 80 | 10 | 90 | 30 |
| | Comp. mov. | 50 | 80 | 40 | 90 | 50 | 40 | 60 | 60 | 90 | 50 | 40 |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7 | vocal exp. fatigue | 70 | 90 | 50 | 90 | 90 | 60 | 90 | 50 | 60 | 90 | 90 |
| | Incr. mov. Int. | 90 | 50 | 30 | 50 | 50 | 40 | 20 | 90 | 40 | 80 | 50 |
| | Comp. mov. | 70 | 90 | 30 | 90 | 70 | 60 | 60 | 30 | 90 | 70 | 70 |

**Table S8: percentage of intervals comparing observations and 11 PSD features for each indicator (vocal expressions of fatigue, compensatory movements, and increased movement intensity) for each participant in the Abduction/Adduction plane. The values are based on percentage of similar intervals between 10 intervals (%).**

| Participant | Indicators | features | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SCCA | SSVL | TACR | SDHC | SH45 | SH135 | SCTA | SHCA | SDTC | SABP | SCRA |
| 1 | vocal exp. fatigue | 60 | 60 | 70 | 60 | 100 | 70 | 80 | 60 | 70 | 70 | 90 |
| | Incr. mov. Int. | 90 | 60 | 50 | 60 | 50 | 50 | 60 | 80 | 50 | 80 | 50 |
| | Comp. mov. | 60 | 90 | 50 | 90 | 50 | 70 | 80 | 60 | 100 | 50 | 50 |
| 2 | vocal exp. fatigue | 70 | 80 | 70 | 80 | 90 | 70 | 90 | 70 | 70 | 80 | 90 |
| | Incr. mov. Int. | 90 | 40 | 30 | 40 | 40 | 50 | 20 | 90 | 50 | 80 | 50 |
| | Comp. mov. | 50 | 90 | 50 | 80 | 60 | 70 | 60 | 50 | 90 | 60 | 70 |
| 3 | vocal exp. fatigue | 50 | 50 | 80 | 50 | 100 | 70 | 100 | 50 | 70 | 70 | 90 |
| | Incr. mov. Int. | 80 | 40 | 30 | 40 | 40 | 20 | 20 | 80 | 20 | 70 | 30 |
| | Comp. mov. | 50 | 80 | 40 | 90 | 30 | 50 | 50 | 50 | 80 | 30 | 40 |
| 4 | vocal exp. fatigue | 80 | 70 | 70 | 70 | 80 | 80 | 90 | 80 | 80 | 80 | 100 |
| | Incr. mov. Int. | 80 | 40 | 40 | 40 | 40 | 50 | 70 | 90 | 50 | 80 | 50 |
| | Comp. mov. | 80 | 80 | 70 | 100 | 70 | 60 | 60 | 80 | 80 | 60 | 80 |
| 5 | vocal exp. fatigue | 50 | 60 | 50 | 80 | 90 | 60 | 80 | 50 | 60 | 90 | 90 |
| | Incr. mov. Int. | 70 | 40 | 30 | 40 | 50 | 40 | 30 | 80 | 40 | 80 | 30 |
| | Comp. mov. | 50 | 90 | 50 | 90 | 70 | 40 | 50 | 50 | 90 | 70 | 50 |
| 6 | vocal exp. fatigue | 90 | 80 | 70 | 80 | 90 | 70 | 100 | 90 | 70 | 50 | 100 |
| | Incr. mov. Int. | 90 | 30 | 40 | 30 | 40 | 20 | 50 | 80 | 20 | 90 | 30 |
| | Comp. mov. | 70 | 90 | 50 | 90 | 50 | 50 | 40 | 70 | 90 | 30 | 40 |
| 7 | vocal exp. fatigue | 50 | 60 | 50 | 70 | 90 | 40 | 100 | 50 | 40 | 80 | 100 |
| | Incr. mov. Int. | 90 | 80 | 70 | 70 | 70 | 80 | 40 | 70 | 80 | 90 | 50 |
| | Comp. mov. | 30 | 90 | 50 | 90 | 50 | 40 | 80 | 30 | 90 | 60 | 70 |

# Curriculum Vitae

| | |
|---|---|
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