Kinematics-Based Recovery Metrics and Inertial Measurement Units to Monitor Recovery Post-Knee Arthroscopic Surgery: A Case Study

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Physiotherapy after lower-limb injury or surgery is essential for recovery of range of motion, functional movement, strength, and return to sport. Clinicians assess patients, prescribe rehabilitation exercises, and monitor progress through recovery phases. Given the bulk of recovery occurs between in-person visits, coupled with regional differences in access to physiotherapy care, remote monitoring of recovery is warranted to improve patient care and recovery.

This work follows the recovery of a patient after arthroscopic partial meniscectomy (APM) surgery, a procedure to remove part of the meniscus in the knee joint. The meniscus is a tissue in the knee joint that improves the articulating surface between the femur and tibia, shock absorption, and transmits force. A conservative estimate puts the rate of meniscal tears at 60 per 100,000, making the APM procedure one of the most common orthopaedic procedures performed. Rehabilitation after APM procedure is generally separated into three phases where the continuation to the next phase relies on meeting the goals of the previous phase as determined by clinician assessments. Assessments are often done through visual observation, manual testing, and goniometric measurements. In a remote setting, these assessments and measurements are challenging to conduct. Wearable inertial measurement units (IMUs) can reconstruct 3D human motion in an unconstrained space, making them a potentially useful tool for remote visualization of therapy exercises and for generating recovery metrics that clinicians can use to inform decision making.

The first part of this work extracts current and exploratory recovery metrics to examine recovery over time, alignment with clinical decisions, and explores novel metrics quantify recovery remotely. Exploratory recovery metrics were extracted based on literature review, clinical input, and incidental findings. Fifty-one (51) recovery metrics were extracted for 5 of the most common rehabilitation exercises: supine heel slide, leg raise, straight line walking, goblet squats, and single leg Romanian deadlifts. Metrics showed strong evidence of recovery if all of the following conditions were observed: improving trends over the recovery period, trends between affected and unaffected limbs, and significant differences. Metrics showed moderate evidence of recovery if two of three conditions were met and weak evidence of recovery if only one or no conditions were met. Of all the metrics examined, 39.2% (20/51) of metrics provided strong evidence of recovery, determined by trends over recovery, between affected and unaffected limbs, and statistical significance. An additional 45.1% (22) of the metrics showed moderate evidence of tracking recovery over time for this case study. Of the 23 exploratory recovery metrics examined, 13 showed strong evidence of recovery and potential for use in tracking rehabilitation.

The second component of this thesis examined the IMU metric error relative to motion capture-based metrics and exercise specific tuning of the IMU algorithm noise parameters. Error between IMU and motion capture metrics being smaller than the effect size, as well as IMU metrics demonstrating similar recovery trends to motion capture metrics, were factors considered when determining the remote monitoring potential using IMU metrics. IMU feasibility was considered strong if both these conditions were met, moderate if only one condition was met, and weak if neither condition was met. Fourteen (14) metrics showed strong feasibility for remote monitoring using the algorithm and another 24 metrics showed moderate feasibility. Tuning the IMU algorithm measurement noise parameters for the heel slide and leg raise showed that increasing gyroscope noise improved heel slide metric error 9.48%, while decreasing gyroscope noise improved metric error for the leg raise exercise by 23.5%.

Finally, a clinician survey was conducted to gather clinician feedback on recovery metrics and stakeholder opinion on future use of the data. As the target primary users of the data presented in this work, 19 physiotherapists participated in the survey. For all metrics they currently use, 95.5% of respondents said they would use the data provided to assist in monitoring recovery. Eight-one percent (81.1%) of respondents said they would potentially use data from exploratory recovery metrics to assist in their clinical decision making, if the data was available. Strength of clinician feedback from the survey was based on the percentage of responses that said they would use the data to inform therapeutic decision making.

This work presents examination of new and existing recovery metrics and a wearable IMU system to monitor recovery remotely using a case study of a patient recovery from a lower limb surgery. Existing metrics provide good indication of recovery, while a subset of exploratory metrics show potential to add valuable recovery information given further validation. Preliminary results indicate that setting exercise specific tuning parameters might have potential for better algorithm performance. Initial clinician feedback on motion capture metrics and future use was primarily positive. Overall, 10 metrics are rated as strong in all two or three categories. Six (6) other metrics were tracked well using the IMU algorithm, however did not show recovery in this case study. Ten (10) metrics showed trends over the recovery period, but only demonstrated moderate success tracking trends using IMUs. Combined, the information presented in this work shows promise in improving patient care and recovery, potentially increasing access to quality care, and transitioning sensor-based human movement reconstruction tools to a clinical setting.

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Chapter 1

Introduction

Physiotherapy practice includes providing treatment to restore and optimize mobility after surgery, injury, disease, and/or degeneration. Based on assessments throughout the recovery process, typically from visual observations of movement, targeted exercises are prescribed to perform at home between clinic sessions [1]. Prompt and continual physiotherapy after an injury or procedure is essential to regain functioning and optimize recovery of the affected area. No treatment and/or sub-optimal treatment can lead to prolonged negative effects, re-injury, or further co-morbidities [2], [3]. Considering regional differences in access to therapy, on-going distancing measures under pandemic conditions, and reliance on subjective self-report in monitoring at-home exercise progress, the need for advancing remote care continues to grow. While technological advances have made remote therapy increasingly accessible via wearable technology and videoconferencing, persistent issues include challenges in assessing recovery with incomplete information, over-reliance on visual feedback and manual assessment that is infeasible remotely, and transition of assessment tools to clinical use [4], [5],[6].

Inertial measurement units (IMUs) can provide pose estimation measures that accurately reconstructs human motion digitally, with the potential for remote use [7]. While these tools provide useful data to therapists via 3D reconstruction of motion and joint trajectories, there is a lack quantitative measures of recovery integral to recovery planning. Even with trajectory information, clinicians are still required to make subjective judgements based on visual information, which may introduce similar errors (e.g., scaling) when viewing an avatar rendering to video call compared to in-person assessment. Applying recovery metrics drawn from the joint kinematic data (with known error) mitigates the subjective quality of therapist assessment, particularly in a remote fashion [8].

Commercial products, such as GaitUp [9] and IMeasureU [10], are capable of extracting metrics from a single IMU for recovery purposes. However, these tools often assess only a few exercises and provide limited recovery metrics. Similarly, IMUs used to assess recovery remotely in research have been constrained to a few movements and provide limited recovery data with a healthy population generally used as test subjects [11], [12], [13]. Considering the V3 model of digital health evaluation [14], there is a need to examine performance of this technology over the recovery process using IMUs to capture clinically relevant measures.

The overall goal of the current research is to provide a patient recovery test case for an existing mobile IMU-based joint kinematic reconstruction method by tracking the rehabilitation of a case study following arthroscopic partial meniscectomy (APM) surgery. The rehabilitation period spans multiple phases with different exercises in different orientations, providing a real-world case study to examine the potential for IMUs to track recovery remotely. Additionally, the purpose of this research is to develop and validate a set of quantifiable rehabilitation exercise metrics from lower limb kinematic data to inform the recovery process following APM (or related knee procedures) and monitor activity remotely. While examining established recovery metrics, this work will investigate the potential for new metrics, not typically assessed in clinic, to track recovery. This thesis aims to bridge the gap between wearable sensor-based kinematic data and clinical practice by providing a spectrum of recovery and performance metrics for an entire set of rehabilitation exercises based on a clinical case study from an APM surgery [15], [16].

1.1 Background

1.1.1 Physical Therapy and Access to Care

Rehabilitation is the process of returning to a healthy level of function or performance using interventions designed to "optimize functioning and reduce disability" in individuals with health conditions [17]. Physical therapy is a broad scope of rehabilitation care provided by health professionals to help patients with physical ailments regain functionality, ease pain, and return to sport [18]. A wide range of clinicians provide therapy to patients including athletics therapist, occupational therapists, chiropractors, and most commonly physiotherapists. In the rehabilitation (or recovery) process, clinicians initially perform assessment(s) to identify the issue(s) and formulate a recovery plan [1].

Treatment plans involve movements and exercises prescribed to the individual to recover healthy range of motion, strength, and any patient or therapist recovery goals. While recovery exercises are performed clinicians observe the patient to ensure they are done correctly and to assess improvement for rehabilitation progression. Clinicians also use verbal feedback from the patient to assess improvement including physiological recovery. Although patients visit therapists in office, the bulk of recovery usually takes place outside the clinic where patients complete exercises at home or at a gym. When patients do see their healthy care provider, they may perform the exercises for assessment, but the information is limited to that day. Physiotherapy care after an injury or surgery is integral to regain function, ease painful symptoms, and return to activity.

Physiotherapists across Canada are not evenly distributed geographically, nor does therapist population density necessarily align with population need or market forces [19]. Physiotherapy use is associated with the distribution of physiotherapists where level of use is positively correlated to the availability of physiotherapists in the community [20]. In a country with high variability in population density, regional differences in access to physiotherapy may negatively impact population health. Demographic differences, specifically age, is a contributing factor in health care access that can be linked to geographic influences [21]. Mobility issues, individual beliefs, and healthcare costs, along with geographical impacts, are all factors effecting unmet needs and access to physiotherapy in the elderly population [21], [22]. For anyone who cannot regularly or easily access in person services, their recovery may take place exclusively at home with video or phone calls with clinicians, potentially in the complete absence of visual assessment or measurements. Remote monitoring with objective measures of recovery would bridge gaps in access and execution of physiotherapy care.

1.1.2 Meniscus, Meniscal Tears, and Treatment

The knee menisci are collagen-based cartilaginous tissue in the knee joint that play a vital role in the articulation of the femur and the tibia [23], [24]. The medial and lateral components of the knee meniscus provide improved articulation surface [25], force transmission and shock absorption in the knee joint [26], and control range of motion at extreme angles while contributing to knee proprioception [27]. The occurrence of meniscus tears is increasing with approximately 60 in 100,000 experiencing injury, although probably a conservative estimate [28]. Meniscus tears are characterized by joint pain and swelling, locking, clicking, or catching of the knee and a feeling of the knee giving out [26]. Surgical intervention is the most common treatment for meniscus tears. Because the meniscus was thought to be a vestigial structure total meniscectomy, the complete removal of the meniscus, was historically the treatment for tears [29]. Treatment evolved to arthroscopic partial meniscectomy (APM) surgery which is the partial resection of the torn meniscus. Recently treatment has moved toward meniscus repair, compared to removal, to mitigate long-term negative effects like increased contact stress and accelerated onsite of osteoarthritis [30], [24]. Nevertheless APM surgery is currently one of the most performed orthopaedic operations worldwide [31].

1.1.3 Rehabilitation Following APM surgery

Table 1.1 shows the best practice protocol based on literature review of post APM surgery rehabilitation protocols [32], [33], [15], [16], [34]. Rehabilitation is primarily split in 2-3 phases corresponding to different goals, where progression to each phase is based on accomplishing the goals of the previous phase. The primary goals of phase 1, usually lasting 1-2 weeks post-surgery, are decreasing pain and swelling, and restoring joint range of motion (ROM). Primary goals of phase 2 are continuing to increase ROM, restoring normal gait patterns, and increasing strength and activation. Phase 3 of recovery is not always included in recovery protocols, where the goals are more related to sport specific movement and maximizing ROM and strength [35]. The execution of this stage depends more on the patient demographic and whether patient goals are to regain functionality or to maximize performance.

Although APM surgery leaves the healthy portion of the meniscus intact, the procedure can still increase contact stress and lead to early presentation of knee osteoarthritis [30]. Short term negative effects include persistent pain, swelling, limited functional movement, and re-injury upon return to sport if healing and rehabilitation are not treated as paramount [2], [36]. Return to sport recovery starts with functional recovery of surgical limb performance. Knee joint range of motion, flexion and extension, and decreased pain and swelling as an indicator of healing, are the primary metrics assessed in the first stage of recovery [2], [16]. Quad lag is visually assessed during single leg raise as the incomplete extension of the knee with flexion of the quadriceps muscles [32], [37]. Weight bearing and gait patterns are monitored and strength exercises begin when full weight bearing and joint range of motion are achieved [2]. Research has suggested that return to sport should be allowed when affected leg quadriceps strength returns to 80% of the contralateral side (as measured by isokinetic testing of quadriceps, using Biodex equipment). However, clinical application of this metric is debatable and limited by possession of a Biodex machine [38]. Strength is often measured through manual muscle testing, where individual or group muscle force is assessed through performance of a movement in the presence of gravity or manual resistance [1].

Table 1.1: Best Practice Rehabilitation Protocol for Recovery from Arthroscopic Partial Knee Meniscectomy

		Protocol Metrics for Progress			
Phase	**Time Period (weeks)**	**Physical Symptoms**	**Range of Motion**	**Activation/Strength**	**Gait Pattern**
A	0-2	Decrease/eliminate inflammation, swelling, and pain	Restore normal hip, knee, and ankle ROM *0-115 degrees and minimum 0 degrees extension to 90 degrees flexion before phase 2	Restore quadriceps activation and muscle control *Goal: no quad lag during SLR	Progressive offloading of crutches until normal gait is restored.
B	2-4/6/8 OR after phase 1	No pain with functional movement	Increase knee ROM, pain free *Week 2 → 0-125 deg Week 3 → 0-135 deg Week 4 → 0-145 deg	Transition to close chain strength exercises. Restore muscle strength, endurance, balance, and proprioception. *Good control with single leg stand and functional movement (including step down, squat, partial lunge)	Restore normal gait mechanics and normal walking pace.
C	6-12 OR after phase 2	No excessive pain or pain with sport specific movement	Maximize ROM	Improved strength and good control for sport specific movement	

1.1.4 Movement and Rehabilitation Monitoring

Depending on the clinic, assessment of recovery in clinic is often limited to visual assessment or goniometric measurements [1]. Goniometers are a joint angle measurement device that isolates a single joint to measure the static joint angle [39]. Goniometric measurements of the hip and knee joints have been associated with an error of 3.92 ° and inter-examiner variance of 3.3° [40]. Others report average error for goniometer measurements was 0° at 90 ° of knee flexion and 3° at 120° of flexion [41]. Goniometers cannot be used when a person is moving which limits the functionality of the tool during physiotherapy exercises involving functional movements. When patients are performing exercises, range of motion and other metric assessments are done visually. Visual assessed joint angle measurements are associated with an average of 5° error [41].

Advances in sensor technology have enabled researchers and clinicians to utilize objective tools for rehabilitation progress and monitoring. Marker-based motion capture digitally reconstructs active or passive markers mounted to body landmarks to visualize joint and body trajectories on screen, permitting objective measurements. Motion capture systems, while useful in laboratory environment, are not always practical in clinics due to equipment cost, space requirements, training, and set-up time.

Inertial measurement units (IMUs) are microelectromechanical devices comprised of accelerometer, gyroscope, and magnetometer sensors that can be used to digitally reconstruct and monitor joint or body motion [42], [7]. IMUs have become increasingly popular in movement monitoring, assessment, and performance, and provide an alternative to motion capture laboratories [43], [7], [44], [45], [46]. IMUs are small, mobile devices that can be attached to body segments to collect movement data and are not constrained to fixed camera locations or wired systems [42] The inclusion of rate sensors in smartphone and wearable technology, such as smart watches, has increased attention on how these sensors can monitor daily behaviours, such as activity tracking [47], [48], [49]. More recently, the focus has shifted to how IMUs can be used in the rehabilitation and physiotherapy space.

Pernek et al used IMUs to measure performance of resistance training exercises using velocity as a measure of exercise performance [43]. They assessed exercises purely based on the speed of the movement, which is not viable for all exercises or rehabilitation movements. A study from Lin et al. used IMUs at the hip, knee, and ankle to estimate lower limb joint kinematics. IMU reconstructions showed good performance compared to gold standard motion capture, with an average joint angle error of 6.20° and 2.73° in the sagittal plane. However, exercise performance using IMUs was not examined [7]. Taylor et al. used 5 accelerometers placed on the lower limbs to monitor 3 lower limb rehabilitation exercises in healthy and osteoarthritic participants. They used an exercise classifier to detect incorrect versus correct performance in the 3 single joint exercises [44]. Although the method reported high accuracy, sensitivity, and specificity, the exercises were limited to single joint, sagittal plane exercises that are used in the beginning stages of physiotherapy and do not expand to further stages of recovery [44]. Another study, from Giggens et al., investigated a single IMU on the thigh to detect incorrect performance of seven single joint exercises with good performance. However, the study was also limited to single joint performing in-plane exercises [45]. O'Reilly et al. examined exercise performance during a squat motion using one body-worn IMU on the torso. While the study determined that one IMU could separate trials based on seven common squat deviations using multi-label classification [46], examining a single exercise limits applicability to typical rehabilitation encompassing a range of exercises.

While the aforementioned studies have assessed the potential of IMUs to monitor movement and exercise performance, their evaluations have focused largely on examining IMU measurement accuracy. As stated above, joint kinematic reconstruction from IMU data has been shown to perform within 6.20° of motion capture joint kinematics. Several studies reviewed in this thesis aimed to provide indications of exercise performance in a binary fashion (i.e., correctly vs incorrectly). Machine learning classification techniques based on

IMU data, has been shown to correctly label exercises as correct or incorrect, including explanations for incorrect exercise performance for feedback. However, using classification techniques limits the labelling to one of the predetermined deviations for exercises. If a patient performed the exercise incorrectly in a novel manner, the information provided using these methods is limited to an incorrect diagnosis. Studies are also limited to single joint exercises, single plane exercises, or only pertain to one rehabilitation exercise. In rehabilitation settings, recovery often occurs over multiple phases comprised of many different exercises multi-plane and multi-joint exercises.

1.2 Objective

Given the diversity of training and rehabilitation techniques, as well as the clinical expertise involved in treating patients, the overarching goal of this thesis is to provide an unconstrained solution to monitoring rehabilitation exercise performance that provides the information clinicians require to properly assess an individual. The following work investigates a range of recovery metrics extracted from wearable 9-axis IMU sensors compared to motion data from a Vicon system. Metrics from the IMU data could be sent to clinicians remotely when the IMU system is used at home, enabling remote tracking of protocol adherence, movement quality, and recovery.

The first objective of this thesis (Chapter 3) was to analyze common recovery metrics and extract novel exploratory recovery metrics to determine their ability to assess recovery. Existing recovery metrics were examined post-recovery to compare between therapeutic decisions made during recovery and objective measurements from motion capture and sensor data. Exploratory recovery metrics, based on literature review, clinical input, and incidental findings were extracted from joint kinematic data. Ground truth data (motion capture data) for these metrics were assessed for rehabilitation tracking potential.

The second objective of this thesis (Chapter 4) was to examine the sensor-based metric data to gauge remote monitoring potential and to examine exercise specific tuning of the sensor algorithm. Error between the motion capture-based recovery metrics and IMU-based metrics was compared to effect sizes to determine clinical validity of IMU sensors to monitor rehabilitation remotely. Then the algorithm noise parameters were tuned based on exercise to explore the potential of exercise specific parameters to minimize the error between ground truth and IMU metrics.

Finally, a clinician survey (Chapter 5) study was completed to gather feedback from clinicians on the data extracted from kinematic data and on exploratory metrics. Data was collected on metrics, clinical decision making during the case study, feasibility of a sensor system in a clinic or at home setting.

The rest of the thesis is structured as follows:

- Chapter 2 presents information on the case study and overarching methods pertaining to all sections of the thesis. Data from the case study was used in all chapters.
- Chapter 3 presents commonly used and exploratory metrics over recovery and assesses the clinical potential of exploratory metrics. The chapter is separated by exercise, for each exercise the metric results are presented in plots. IMU and motion capture data was presented on the same plot for metrics, however in Chapter 3 motion capture data only is used to assess the metrics for recovery tracking potential. After metrics are presented, a Clinical Discussion section presents statistical tests to determine significant change over recovery and discussion of results.
- Chapter 4 analyzes the metric error between ground truth and experimental data and relates this to effect size over recovery and between limbs. Exercise specific EKF tuning results are presented and discussed.
- Chapter 5 reports the survey data and results including clinician feedback on recovery metric data, therapeutic decisions, and feasibility of remote monitoring of rehabilitation. Direct feedback is presented in the form of written responses.
- Chapter 6 summarizes the contributions in this thesis and discusses limitations and future work.

Chapter 2

Methods

2.1 Data Collection

2.1.1 Case Study and Patient Information

This research follows a case study using a longitudinal data set collected on a 22 year-old elite female volleyball player recovering from arthroscopic knee partial meniscectomy (APM) surgery, with the goal of recovering to peak performance. The procedure was performed on the right (affected) leg only, removing a portion of the meniscus in the knee. Rehabilitation sessions were divided between: 1) clinic sessions with an athletic therapist, 2) at home, and 3) in a motion capture lab as part of the 'at home' sessions. The entire recovery period was 15 days (day 1 post-surgery to return to play) and included 19 rehabilitation exercises prescribed by an athletic therapist. A therapy session was also collected 1 year post surgery, representing performance from the recovered patient. At one year post-surgery one set of each exercise was performed in a motion capture lab and practice sets were not allowed. The case study patient information and patient history is presented in the following lists.

(A) Patient Information:

- Age: 22
- Gender: Female
- Height: 183 cm
- Weight: 83.9 kg
- Injury: Tear in the posterolateral meniscus

- Treatment: Arthroscopic partial meniscectomy surgery to remove the torn portion of the lateral meniscus of the knee

(B) Patient History:

- Varsity volleyball player at USPORTS level
- Anterior cruciate ligament (ACL) tear 24 months prior on the same knee (right)
- ACL reconstruction surgery 16 months prior
- Recovered fully from ACL surgery and returned to play
- Played for 4 months before tearing the knee meniscus while landing from a jump
- APM surgery 5 months after tearing meniscus
- Returned to practice 15 days after APM surgery

The case study rehabilitation protocol, shown in Table 2.1, follows a similar protocol as described in Table 1.1, with the exception of the actual time frames for each phase. The case study patient progressed more quickly than the typical patient population. The case study protocol was generated in interviews with the supervising athletic therapist.

Table 2.1: Case Study Rehabilitation Protocol for Recovery from Arthroscopic Partial Knee Meniscectomy

			Protocol Metrics for Progress			
Phase	**Protocol #**	**Time Period (weeks)**	**Physical Symptoms**	**Range of Motion**	**Activation/Strength**	**Gait Pattern**
1	Case study	0-0.5	Control pain and swelling	Restore hip, knee, and ankle ROM		
2	Case study	0.5-1	Avoid excessive joint pain (focus on strength + walking)	Continue to improve ROM (focus on strength + walking)	Regain quadriceps strength and coordination Return to close chain strength exercises	Walk w/out limp
3	Case study	1-2	Minimal joint pain in sport movement	Maximize ROM to healthy	Perform normal strength exercises	Normal gait and hurdle gait (toe clearance)

The following study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB 41314).

2.1.2 Motion Capture

Motion capture data were collected in a research lab with a Vicon motion capture system using Vantage cameras for marker capture and Vue cameras for video data. Passive motion

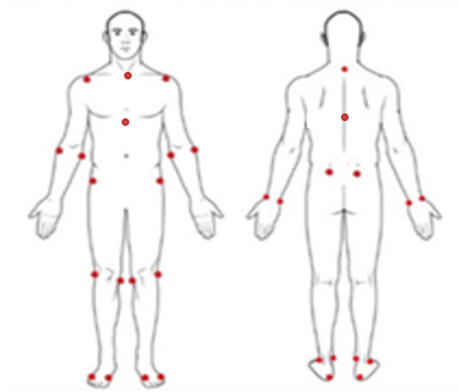

Figure 2.1: Vicon motion capture marker layout.

capture markers were placed on the lower body of the subject using a modified Helen Hayes marker layout. Figure 2.1 shows the marker layout using red dots to indicate the placement of the markers. The 33 body markers were:

- Right leg (7): Right knee medial, right knee lateral, right ankle medial, right ankle lateral, right foot medial (2nd toe), right foot lateral (5th toe), right heel
- Left leg (7): Left knee medial, left knee lateral, left ankle medial, left ankle lateral, left foot medial (2nd toe), left foot lateral (5th toe), left heel
- Torso (8): Right ASIS, left ASIS, right PSIS, left PSIS, T10, C7, sternum jugular ('STERN'), sternum xiphisternal ('DIAPHRAM')
- Right arm (5): Right shoulder, right elbow medial, right elbow lateral, right wrist medial, right wrist lateral
- Left arm (5): Left shoulder, left elbow medial, left elbow lateral, left wrist medial, left wrist lateral

Motion capture was collected at 200 Hz and marker trajectories were manually cleaned using Vicon Nexus software labelling and gap filling techniques.

2.1.3 Sensor Data

Custom made 9-axis mobile inertial measurement units (IMUs) were used to collect sensor data during the case study. The IMUs were individually powered and streamed raw data via Bluetooth to a tablet. Sensors were attached to a top plate with 3 Vicon markers to provide initial orientation of the sensors (in the clinic this initial position would be set as a specific orientation, i.e. standing upright). Seven IMUs were attached tightly to the body via Velcro straps, with the following placement instructions:

- One sensor was placed on the front middle of the lower torso, approximately between the right and left ASIS
- one sensor was placed three finger widths above the middle of the knee cap on each thigh
- one sensor was placed just above the ankle on the anteromedial flat bony surface of each shank
- one sensor was placed on the dorsal aspect of each foot

IMU data was collected at 100 Hz and stored in time stamped files. A data collection list stored the linked exercise collections with the corresponding IMU file timestamp.

2.2 Collection Protocol

The data follows real-time recovery of a patient during the 15 day rehabilitation period following APM surgery. After this time, the patient/subject returned to varsity practice and was no longer monitored. Table 2.2 shows the collection schedule. The data presented in this thesis is from rehabilitation sessions performed in the motion capture lab (column two in Table 2.2). The sessions are highlighted in the corresponding color of recovery phase in the case study protocol in Table 2.1 and the case study exercise protocol in Table 2.3. Phase A exercises were done on day 2, day 3, and day 6. A combination of phase A and phase B exercises were done on day 3 and day 6 and phase C exercises were done on day 7, 8, 14, and 15. Day 14 was excluded from analysis because of excessive noise in the motion capture collection. A collection of all recovery exercises was done at one year post-surgery as a healthy baseline.

Table 2.3 shows the exercises prescribed by the athletic therapist for each phase of recovery and separated according to recovery goal. Data was collected for each set of exercises performed. Vicon recording was initiated, followed by the IMU collection platform. The subject performed a calibration exercise denoting the start of the collection, which changed depending on the physical capabilities of the patient at the time of recovery (purely for the time syncing of motion capture and IMU data). The subject then performed one set of one rehabilitation exercise, followed by a pause, and the calibration exercise. IMU streaming was then terminated followed by Vicon. The process repeated for each set of rehabilitation exercise performed that day. Although sensors were worn during rehab the data presented in this work was not provided to the clinician at the time, avoiding bias in therapeutic decision making real time.

	Day Post-Surgery	Exercise Set Performed
Location		Motion Capture Lab
Modality		MOCAP + IMU
	-1	**A/B mix**
	1	
	2	**A**
	3	**B/A mix**
	4	
	5	
	6	**B**
	7	**C**
	8	
	9	**C**
	14	**C***
	15	**C****

* MOCAP data on day 14 excessive noise

** IMU data was not collected on day 15

Figure 2.2: Case study data collection schedule post-procedure.

Exercises analyzed for phase A and B of recovery were supine single leg heel slide, supine single leg raise, and overground straight line waking. While the scope of this study is limited to the APM procedure, the selected rehabilitation exercises are also prescribed for other common orthopedic procedures, including anterior cruciate ligament (ACL) reconstruction [50], total hip arthroplasty (THA) surgery [51], and total knee arthroplasty (TKA) [52]. Analysis and findings of clinical utility of existing metrics for these exercise, exploratory metrics for these exercises, and remote monitoring capabilities of the wearable IMU sensor system can be applied to all these procedures as well. Exercises analyzed for phase C of the rehabilitation protocol, highlighted in green in Figure 2.3, were the double leg goblet squat and the single leg Romanian deadlift exercises. These primary exercises for regaining strength and activation in phase C and are the first weight bearing exercises prescribed post-surgery besides walking. Both are also common exercise prescribed after lower limb orthopaedic procedures [52], [50].

At each collection pain and fatigue scores were recorded before each session, after each exercise, and after the therapy session was complete. Pain is recorded as pain in the affected leg at the time of performing the exercise. Pain scores for the single leg exercises on the unaffected leg reflect pain felt in the affected leg. Fatigue scores refer to fatigue scores in the affected limb. The 10 point Numeric Pain Rating Scale (NPRS) [53] was assessed verbally, the researcher asked the subject the following question:

- "Rate your pain/fatigue on a scale from 0 to 10, 0 being no pain/fatigue at all and 10 being the worst pain/fatigue you have ever felt."

		Protocol Exercises		
Phase	**Time Period (weeks)**	**Range of Motion**	**Activation/Strength**	**Gait Pattern**
A	0-0.5	• Pendulum swings • Active Knee Extension • Ankle Pumps • Supine Heel Slide • 4 Way Hip Movement	• Supine Single Leg Raise • Side Lying Clam • Side Lying Single Leg Glute Rainbow	• Straight Line Walking w. Crutches • Straight Line Walking • Obstacle Walking (Walking over Hurdles)
B	0.5-1	• Pendulum swings • Supine Heel Slide • 4 Way Hip Movement	• Side Lying Clam • Side Lying Single Leg Glute Rainbow • Single Leg RDL • Quarter Squat • Squat to 90 °	• Straight Line Walking • Obstacle Walking (Walking over Hurdles)
C	1-2	• Biking	• Side Lying Single Leg Glute Rainbow • Single Leg RDL (with weight) • Banded Double Leg Glute Bridge • Goblet Squat (full range) • Goblet Squat (with weight) • 4 Way Banded Monster Walks	

Figure 2.3: Case study exercise protocol separated by goals of recovery in each phase

2.3 Data Processing and Analysis

MATLAB (R2021a, Mathworks, Natick, MA, USA) was used for all data processing. Joint angles from the motion capture data and the IMU data were separately calculated using a previously developed and tested extended Kalman filter sensor fusion with a 35 degree of freedom (DoF) full body kinematic model [7], [54], [55]. The algorithms are used in this work for a different purpose with a different subject population. The MATLAB function findpeaks [56] was used to segment repetition events from joint angle trajectories, using motion qualities characteristic to each exercise. Spatiotemporal metrics were extracted for each repetition and exercise on each day of rehabilitation. Recovery metrics (e.g., range of motions, peak angles, repetition time) and movement performance metrics were averaged for each day of recovery to monitor recovery progression.

Chapter 3

Analysis of Existing and Exploratory Recovery Metrics

3.1 Introduction/Background

Recovery metrics, or measures, provide indicators for clinicians to progress recovery and rehabilitation exercises. In clinic settings, measures are often assessed visually and through self-reported feedback from the patient. Measurement tools (e.g., goniometer) are sometimes used to measure metrics, however are limited to in person clinic use.

Figure 3.1 lists the primary metrics or exercises that were used by the athletic therapist in this case study to progress the patient to the next phase of recovery. Although all the exercises listed in 2.3 are performed as part of recovery, a few key exercises were used as primary assessment for progression. The supine heel slide exercise is primarily used to assess the kinematic goals of recovery joint range motion to progress to phase B. Note, decreasing pain and swelling is also a primary goal of phase A, assessed through verbal feedback and visual observation in person. The supine single leg raise and straight line walking were the primary exercises used to progress the patient from phase B to phase C. Recovering quadriceps activation and strength, assessed through supine straight leg raise, and walking with normal gait patterns or no limp, assessed through straight line walking, were the progression criteria.

Progression past phase C and to the end of rehabilitation was determined by return of full ROM with no pain, return of strength and activation in the affected limb, and the ability to perform all exercises with no pain and stability. The primary recovery exercises used to assess strength and activation are the goblet squat and the single leg Romanian dead lift. These exercises were performed without weight, and extended using 25 pound weights when the supervising clinician approved the transition to weighted exercises.

	Phase A (Week 0-0.5)	Phase B (Week 0.5-1)	Phase C (Week 1-2)	End Rehab
Progression Criteria	- Heel Slide (Joint ROM)			
		- Quadriceps Strength (SLR) - Walking w/o Limp - Squat to 90 w/o Pain		
			- Return of Strength/Activation - Full ROM Squat w/o Pain	
				- Return of Strength - All Exercises w/o Pain - All Exercises w. Stability

Figure 3.1: Progression Criteria for Each Phase of Recovery

Recovery metrics extracted from joint kinematic trajectories for lower limb joints are presented in this chapter, separated in section by each primary exercise used to assess progression. All metrics are presented in plots showing the progression over time. Existing metrics, i.e. metrics currently used by clinicians are presented first, followed by exploratory metrics. Exploratory metrics are extracted to examine progression over rehab and therefore the potential for tracking recovery goals that are difficult to assess in person or using kinematic data. Exploratory measures are measures generally not used currently by clinicians, either because the clinician is unable to measure the metric, it is generally believed the metric is unable to track recovery, or there is not enough supporting literature to prove a metric is important in recovery. The emphasis here is to explore different metrics using data from an affected patient to provide preliminary evidence of exploratory metrics ability to track recovery progress and potentially indicate their importance or additional insight in recovery. It is important to note that while exploratory metrics might not show significance in this case study, this work covers only one type of surgery that does not cover the entire scope of all lower limb surgeries or injuries. Existing and exploratory metrics were generated based on literature review of different kinematic relationships and strength recovery, professional input, and incidental findings in the data.

3.2 Methods

The following presents how metrics were extracted for general subsets of recovery metrics (i.e. range of motion metrics) and how metrics are labelled. When details are not provided here, additional information is given when results are presented.

ROM Metrics: Joint ROM refers to the amount of motion that occurs at a joint and is typically reported as a range from the minimum to maximum anatomical angle the joint can reach [1]. For example, the normative sagittal plane range of motion for the knee joint in females aged 20 to 44 is [-1.6°− 141.9°] [57], where -1.6°means 1.6°extension and 141.9°is flexion. The entire average angular deviation would be 143.5°. In this work, total angular deviation measurements are referred to as joint range of motion metrics for simplicity. When flexion or extension angles are presented these are the maximum values of either flexion or extension during a repetition. Assessment of joint ROM is a fundamental clinical outcome measure during rehabilitation [58], [59]. ROM was reported for joints of interest and in planes of interest specific to different rehabilitation exercises as the difference between the maximum and minimum values during on repetition.

Temporal Metrics: Temporal metrics are generally not objectively assessed during therapy in terms of measuring the time using a stop watch. In the case study, the participant were asked to perform exercises at a comfortable speed with little instruction, therefore temporal metrics were not objectively assessed as indicator of recovery. These metrics, mainly repetition time, indicated comfort during the exercise and may be associated with pain and fatigue scores. Repetition time, time ratios between movement directions, and time offsets in in joint movements were part of a battery of temporal metrics extracted from the kinematic data to assess their potential for recovery outcome measures, the alignment with pain and fatigue scores, and the potential for new metrics to track recovery. Additionally, although it is not objectively measured, repetition time could provide indications of proper exercise performance and comfort levels remotely, when patient and visual feedback is limited. Repetition times for exercises were extracted from the elapsed time between peaks that distinguish the motion. Different time ratios were calculated as the time elapsed during one part of the exercise divided by the time for the second part of the exercise. Time offsets were the calculated difference in time between two separate occurrences in a repetition. Specific metrics are described in more detail when presented in the following chapters.

Asymmetry Index: Asymmetry index (percentage) was used to assess bilateral symmetry in different measures during gait. Step length and width asymmetry indices were calculated using Equation 3.1.

$$ASI = \frac{abs(\bar{\mathbf{l}}_{left} - \bar{\mathbf{l}}_{right})}{\max(\bar{\mathbf{l}}_{left}, \bar{\mathbf{l}}_{right})} * 100\% \tag{3.1}$$

where $\bar{\mathbf{l}}_{left}$ is the mean step length or width for the left leg and $\bar{\mathbf{l}}_{right}$ is the mean step length or width for the right leg. Steps were identified by finding occurrences of maximum distance between the left and right feet positions. For motion capture data, geometry between the Cartesian coordinates of the left and right feet and a third point indicating the direction of travel were used to calculate step length and width.

For the IMU sensor data, drift was observed about the vertical axis which challenges our metric extraction algorithms. To extract step length, both hip internal/external rotation and hip abduction/adduction data were zeroed to produce straight walking by only allowing flexion-extension at the hip joint. The Cartesian distance between the two feet in sagittal plane corresponded to the step length. Because hip frontal and transverse plane motion was zeroed step width remained constant each step and could not be compared to ground truth. This was only done to extract step length for walking trials. Straight line walking was done in a motion capture studio with limited space for long distance walking and on the days walking was assessed, walking long distances was difficult for the patient. First and last steps were excluded from the analysis.

Statistical Analysis and Metric Comparison: Metrics were primarily evaluated using threshold analysis based on confidence intervals for healthy data and changes in mean values over the recovery period. Error bars for mean data points represent two standard deviations from the mean. For single leg exercises, 95% confidence intervals for healthy data are represented by the shaded areas that cover the mean ± 2 standard deviations, for all repetitions on the unaffected (non-operated) leg over recovery. Metrics that utilized data from both legs were evaluated by comparing to healthy data collected one year post surgery. Single leg metrics were evaluated by comparing to the non-surgical leg metrics and healthy data on the same leg collected one year post surgery.

Two-tailed unpaired t-tests, with significance at $p < 0.05$, were used to determine changes in recovery metrics. Welch's t-test was used where the variances between groups were not similar. Two-sided t-tests were used because directionality was not guaranteed between groups. T-tests were performed between the affected leg (right leg) and the unaffected leg (left leg) on the first day the exercise is prescribed in the protocol and the last day the exercise is in the protocol. Comparing significant difference between legs on these two days provided indication of the affected leg reaching the performance of the unaffected leg over time and continued disparity between the two sides when the exercise was taken off the recovery protocol. Two t-tests were also performed on the affected leg only: between the first day the exercise was in the protocol and the last day the exercise was in the protocol, and between the last day the exercise was in the protocol and one year post-surgery. These tests provided an indication of significant recovery of the affected leg over time compared to itself and also whether there was a significant deficit compared to one year later.

3.3 Supine Single Leg Heel Slide

The supine single leg heel slide is a key recovery exercise in the beginning phase of rehabilitation where the primary goal is to recover ROM in the knee joint. The patient lies supine on the ground or table with both legs fully extended and lying flat on the surface. The exercise is performed on one leg at a time, keeping the heel on the surface while repeatedly flexing and extending the knee, moving at a comfortable pace. Figure 3.2 demonstrates how the exercise is performed [60].

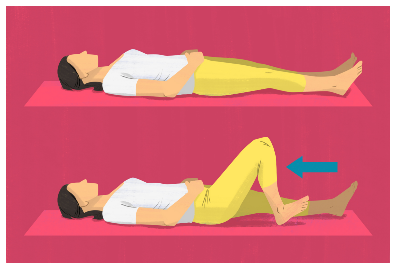

Figure 3.2: Graphic illustrating the supine single leg heel slide, beginning pose demonstrated in the top image and the movement shown in the bottom image (knee flexed).

Key recovery metrics assessed in clinic for this exercise include peak knee flexion and knee extension angles, and knee ROM. Currently, clinicians either observe knee ROM or measure the change in knee angle using a goniometer to progress a patients recovery. Knee ROM reaching acceptable range (with little-to-no pain), either close to the unaffected leg or healthy population values, provides indication that the affected joint ROM is recovered and rehabilitation exercises can progress to weight bearing exercises. Heel slide was included in the recovery protocol from day 1 to day 6 post-surgery, when it was removed from the exercise regimen. There are data collection days for heels slide on day 2 post-surgery, day 3 post-surgery, and day 6 post-surgery. On day 6 the therapist determined that the individual had performed the rehabilitation exercises adequately and the goals of the first two phases had been met and the protocol progressed to phase C. Pain and fatigue scores during each set of the exercise on each day of collection were recorded and presented in Table 3.1 below.

Candidate recovery metrics assessing supine single leg heel slide were: knee ROM, knee extension angle, knee RMS sagittal plane angular velocity, knee RMS sagittal plane angular acceleration, repetition time, and time ratio between extension time and flexion time. Knee ROM metrics and repetition time are metrics typically assessed by clinicians, whereas angular rate metrics and time ratio metrics are considered exploratory, are not typically assessed, and were not assessed by the clinician in this case study.

Table 3.1: Pain and Fatigue Scores Recorded During Supine Heel Slide

	Day 2		Day 3		Day 6	
	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue
Heel Slide Right Leg (affected leg)	2	6	1	0	3	0
Heel Slide Left Leg (unaffected leg)	0	6	0	0	0	0

3.3.1 Existing Metrics

Existing metrics used by clinicians, assessed visually (or goniometer) while patient performed the exercise, were knee ROM, knee extension angle and repetition time. Figure 3.3 presents the mean knee sagittal plane ROM on the associated recovery day post-surgery. Blue and red data points present the ground truth (MOCAP) data for the unaffected and affected leg respectively, while yellow and purple lines indicate the sensor-derived (IMU) metrics for the same legs. The grey shaded area shows the 95% confidence interval (CI) for the unaffected leg across all recovery days. The mean knee ROM of the affected leg increased by 36.45% from Day 2 to Day 6 post-surgery (88.91° ± 7.39° to 121.32° ± 2.37°). Comparatively, the mean knee ROM on the non-operated leg across all days (grey shaded area) in 3.3, was 129.22° ± 6.44°. Knee ROM of the affected leg on day 6 remained 4.11° smaller the 95 % CI of the unaffected leg.

Figure 3.4 shows mean maximum knee extension angle over the recovery period. Although heel slide is primarily used to recover knee flexion, it is also important to reach a healthy level of extension. Positive values on the y-axes show knee extension, while negative values mean the knee stayed in flexion even at the most extended point. Maximum knee extension is reached at the beginning and end of each repetition. Unlike knee ROM, knee extension angle does not demonstrate a similarly clear trend from day 2 to day 6. Max knee extension angle stayed consistent through the recovery period. The affected leg was within the CI for the healthy leg for all days except day 3 when the average maximum extension angle was 3.03 ° larger than the healthy leg. Referring back to Table 3.1 pain scores decreased from 2/10 on day 2 to 1/10 on day 3, potentially explaining the reason for increased knee extension on day 3 post-surgery.

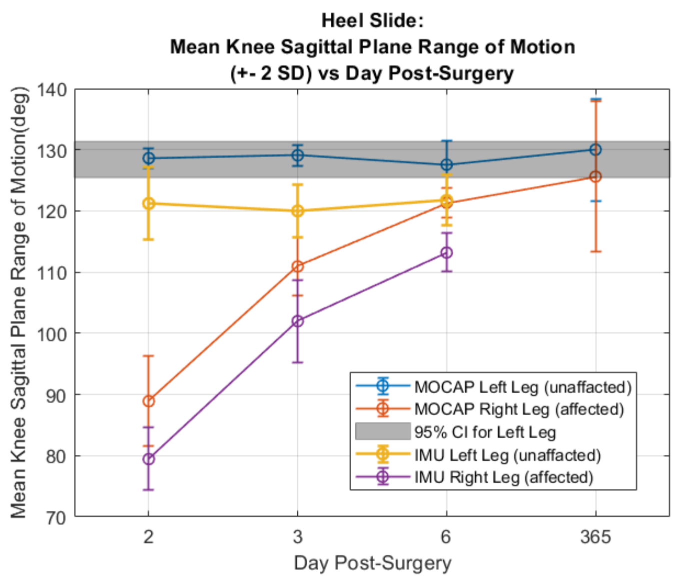

Figure 3.3: Mean knee range of motion during single leg supine heel slide on each collection day post-surgery (±2SD).

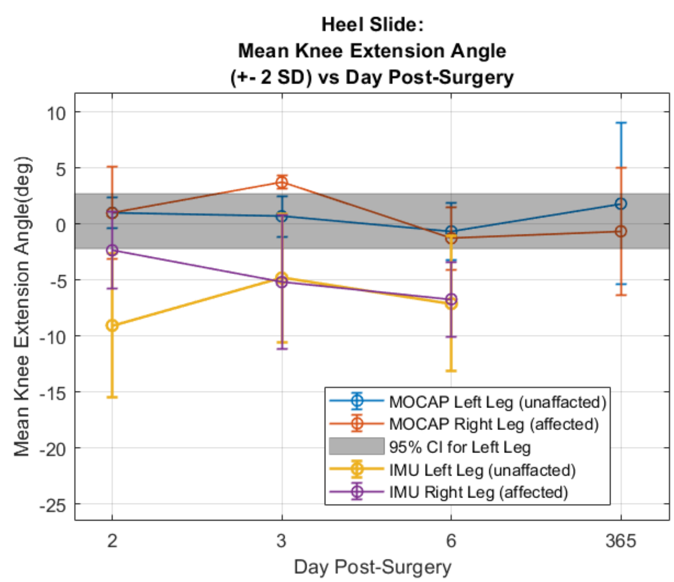

Figure 3.4: Mean knee extension angle during single leg supine heel slide on each collection day post-surgery (±2SD).

Mean repetition time on each day post-surgery for the heel slide exercises is presented in Figure 3.5. Repetition time is presented as a mean with 2 standard deviation error bars on either side for the affected and unaffected legs. The red line shows the mean repetition time on each day for the affected leg and the blue line shows the average repetition time for the unaffected leg. Mean repetition time for the heel slide on the affected leg decreased from 6.62±3.98s on Day 2 to 3.92±1.52s on Day 6 and fell within the 95% confidence interval of the unaffected leg (3.32±1.35s). Variability in mean repetition time decreases throughout recovery and is lowest on Day 6, indicating an increasingly consistent performance. Fatigue scores for the affected leg in Table 3.1 decrease from 6/10 on day 2 to 0/10 on day 3, and the exercise was performed until fatigued on the final day. Repetition time, while not the primary goal of this exercise, could provide insight on pain and fatigue levels and ease of motion. Verbal feedback from the patient is generally used to assess comfort, however using repetition could provide objective insight remotely.

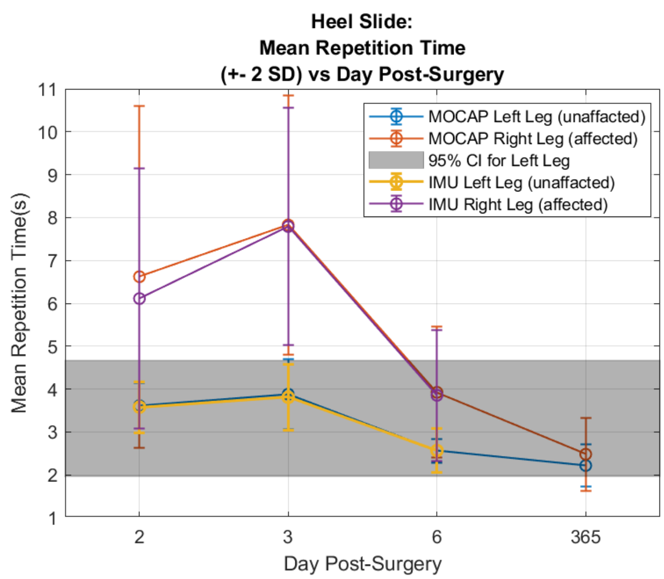

Figure 3.5: Mean repetition during the supine single leg heel slide on each collection day post-surgery (±2SD).

3.3.2 Exploratory Measures

Due to difficulty in measuring or lack of tools, velocity and acceleration measures are typically not assessed by clinicians. Additionally, during phase A and B, recovering joint ROM and pain-free movement is generally deemed more important than speed of movement. Recently, velocity-based training (VBT) has become an increasingly popular method of assessing movement performance. The concept behind VBT is that the speed of a movement with a given submaximal weight can provide good indication of maximal strength [61]. Although primarily used when strength training healthy subjects, VBT is suggested to indicate strength and power over time, and could inform exercise prescription over the recovery period [61]. Considering kinematic data is the only information available, these exploratory measures of angular velocity and acceleration were extracted to determine if they could provide insight into early stages of power and strength recovery.

Root mean square (RMS) angular velocity is presented in Figure 3.6. Angular velocity increases from $35.0°/s \pm 12.78°/s$ on day 2 to $77.1°/s \pm 19.8°/s$ on day 6. For the left (unaffected) leg, mean RMS angular velocity also increases from day 2 to day 6 by $32.8°/s$. However, on day 6 a difference between left and right legs of $46.3°/s$ is observed. Furthermore, the right leg performance did not fall within two standard deviations of the left leg 95% CI for that day. One year post-operation, the deficit between the right and left knees decreased to $19.3°/s$ and the average RMS angular velocity on the right side falls within the 95% CI for the left leg.

Figure 3.7 shows similar recovery trends for RMS knee angular acceleration. The affected leg angular acceleration stays lower than the unaffected leg and outside of two standard deviations for each day of recovery, while the unaffected leg does increase from day 2 to day 6. For both angular velocity and angular acceleration, the mean day 6 values fall within the 95% CI for all unaffected days (shaded area). Although the left and right leg angular velocity and acceleration increase similarly from day 2 to day 6, there is still a deficit between the right and left legs on day 6. Contrarily, the deficit is much smaller between right and left legs at day 365 post-surgery. This could indicate a deficit in recovery of strength in the early stages of rehabilitation. While strength is generally not the main goal of phase A, recovery of activation was assessed in the leg raise exercise in phase A of this case study and may be an important aspect to consider in such a short recovery period. These metrics will be investigated further in later phases of rehabilitation when primary goals are recovery of strength.

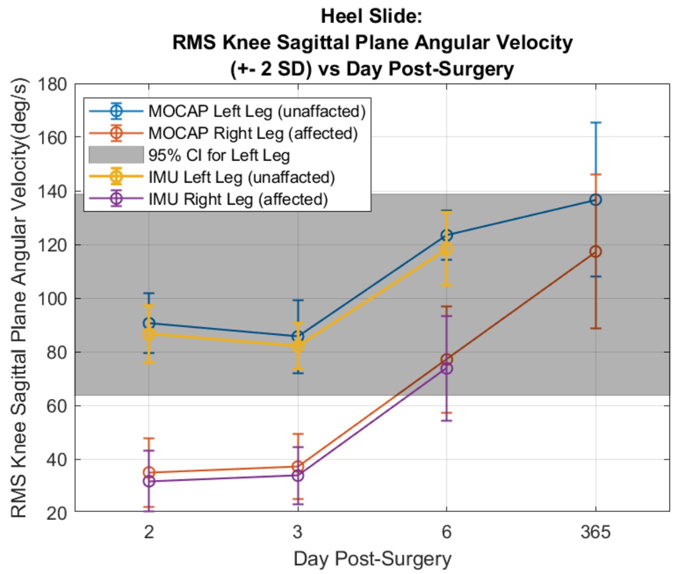

Figure 3.6: Mean knee joint RMS angular velocity during supine single leg heel slide for each collection day post-surgery (±2SD).

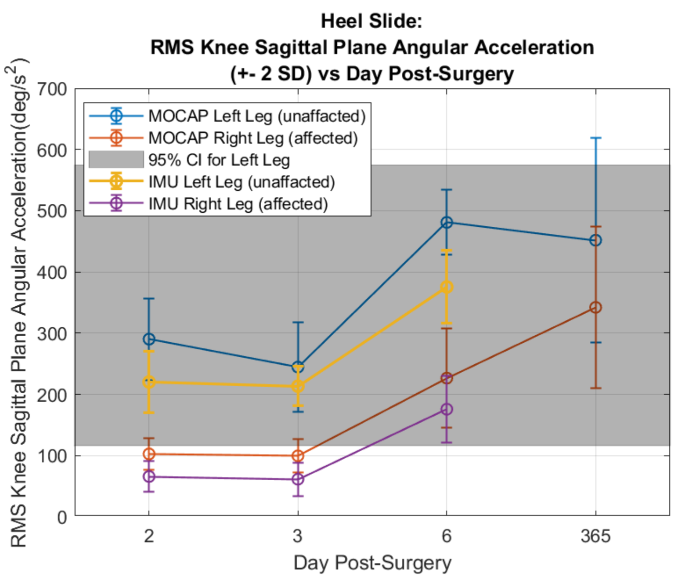

Figure 3.7: Mean knee joint RMS angular acceleration during supine single leg heel slide for each collection day post-surgery (±2SD).

A third exploratory metric, the time ratio of extension time to flexion time, is shown in Figure 3.8. This metric was extracted based on an incidental finding in joint trajectory data, in an effort to quantify symmetry of antagonist movements. The start and end of exercise repetitions were labelled using the positive peaks in knee joint angle, corresponding to the moment of maximum knee extension when the leg (i.e., lying on the table). Flexion time was the time from the start of the repetition to the time of maximum knee flexion angle (i.e., negative peaks in the knee angle trajectory). The corresponding extension time was the time from the same peak flexion point to the end of the repetition, labelled as the next positive peak in knee joint angle. A time ratio greater than one indicates the subject spent more time in extension than flexion, whereas a ratio of less than one indicated the subject spent more time in flexion than extension. A time ratio of one indicates the same amount of time was spent in flexion and extension.

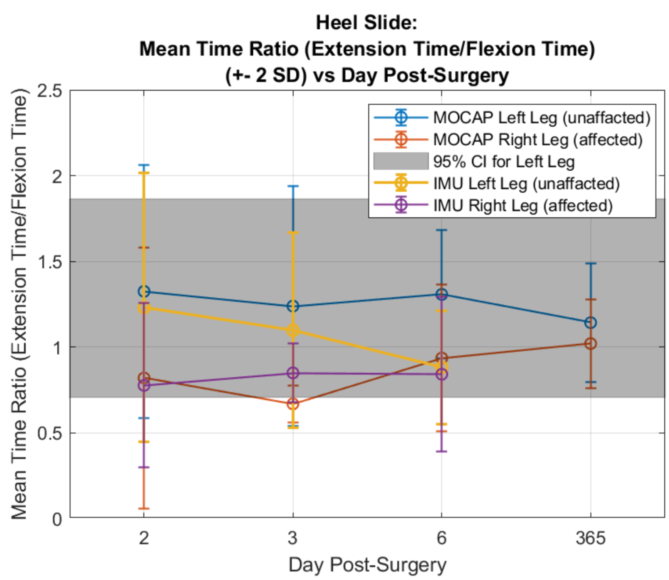

Figure 3.8: Time ratio of extension time to flexion time on each day of collection post-surgery during heel slide (±2SD).

Over the recovery period, mean time ratio for the affected leg increased from 0.820±0.760 to 0.937±0.426, moving closer to a value of one. Mean time ratio for the affected leg tended to be smaller than the mean time ratio of the unaffected leg on each day of recovery, and smaller than 1 on all days post-surgery before reaching a value of 1.02±0.258 on day 365. In contrast, the unaffected leg time ratio is greater than 1 on each day including day 365. This means the unaffected leg generally spendt greater time in extension, a motion in the direction of gravity. The recovery profile of the affected leg indicated the participant spent more time in flexion, likely associated with the added challenge of opposing gravity. In contrast, the unaffected leg does not show the same trend. Therefore, this measure could provide a good indication of recovery and potentially a good indication of strength recovery.

3.3.3 Supine Heel Slide Discussion

P-values for unpaired two-tailed t-test for each metric are presented in Table 3.2. Significant increase in knee ROM of the affected leg was found between day 2 and day 6, indicating that knee ROM was recovered. Knee ROM was significantly different comparing affected and unaffected legs on day 2 and day 6 post-surgery. Combined with the ROM not reaching the mean $\pm$ two standard deviations of the unaffected leg on day 6, as seen in Figure 3.3, sparks the question of whether knee ROM was sufficiently recovered to eliminate this exercise from the recovery protocol at this time.

Table 3.2: Unpaired Two-Tailed T-test P-Value for Single Leg Heel Slide, Between Affected Leg Over Recovery and Between Affected and Unaffected Legs

	Affected vs Unaffected Leg		Affected Leg	
	Day 2	Day 6	Day 2 vs Day 6	Day 6 vs Day 365
ROM	<0.001	<0.001	<0.001	<0.001
Extension	0.973	0.371	0.047	0.586
RMS Angular Velocity	<0.001	<0.001	<0.001	<0.001
RMS Angular Acceleration	<0.001	<0.001	<0.001	<0.001
Repetition Time	0.012	<0.001	0.006	<0.001
Extension/Flexion Time Ratio	0.084	0.002	0.504	0.632

Knee extension angle showed a significant decrease on the affected leg between day 2 and day 6, although the extension angle stayed within the 95 % CI for the unaffected leg and was only 0.616° smaller than the unaffected leg on day 6. Knee extension angle showed no significant change over recovery and any change was less than the reported error using goniometers or visual measurements [40], [41]. Measuring knee extension angle changes or noting improvement in clinic in this case study was done visually and may not be accurate. Although knee extension angle was greater than 0° most days and there may not be a deficit in extension, where normative range of extension is 1.6° [57]. Similar to ROM, RMS angular velocity and acceleration show significant differences in all tests. There exists a deficit between the left and right sides even on day 6 of recovery, although the affected leg does improve over the first week the exercise was performed. These recovery metrics might provide more insight into recovery and show significant changes in performance. Repetition time also shows significant changes in all four tests. Like angular velocity and acceleration, repetition time is not generally assessed in practice. However, repetition time could provide a good first indication of strength, power, and/or comfort. Extension to flexion time ratios were within the 95% CI for the healthy limb, however there was a significant difference between the affected and unaffected limbs on day 6 post-surgery, when the difference between the limbs was the smallest over all recovery days. Significance tests provide inconclusive results to show improvement over time, but the difference between limbs might indicate that this metric could be used in exercise assessment.

3.4 Supine Straight Single Leg Raise

The supine single straight leg raise (leg raise) is the second exercise commonly used in lower limb rehabilitation. Figure 3.9 demonstrates the exercise motion [62]. The initial position is the leg drawn with a dotted line. The subject moves the leg to the position in the air (solid line). The subject then returns to the initial position, which is one repetition. The purpose of this exercise was to recover quadriceps activation by keeping the knee straight throughout the motion. Clinicians assess this exercise using visual cues, such as flexing of the quadriceps and estimating the knee joint angle through the motion. In both phase A and phase B exercise protocols, leg raises were conducted on day 2, day 3, and day 6 post-surgery, as well as one year post-surgery.

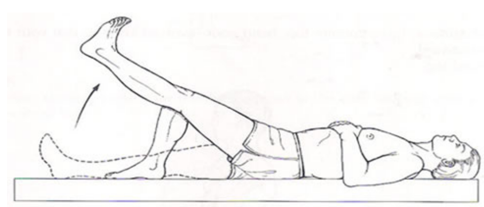

Figure 3.9: Illustration of the supine single straight leg raise, initial position (dotted line), and motion (solid line).

Pain and fatigue scores during each set of leg raise exercise are listed in Table 3.3. The subject had little-to-no pain with this exercise on all days except day 6 post-surgery when pain was 1/10. Some pain is expected considering the knee is not moving during this exercise, requiring consistent quadriceps activation. Fatigue scores were high during the leg raise on day 2, and decreased to 0 on day 3. On day 6, fatigue scores increased on the affected leg, while fatigue was a 0/10 on the unaffected leg for day 6.

Table 3.3: Pain and Fatigue Scores Recorded During Supine Single Straight Leg Raise

	Day 2		Day 3		Day 6	
	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue
Leg Raise Right Leg (affected leg)	0	6	0	2	1	6
Leg Raise Slide Left Leg (unaffected leg)	0	6	0	2	0	0

3.4.1 Existing Metrics

Metrics used in clinic extracted from kinematic data were knee ROM, max knee flexion angle, max knee extension angle, and hip ROM in each plane. Hip ROM was not assessed as a recovery metric; however, it demonstrates how this tool may be used to remotely monitor correct exercise performance. Mean repetition time was also presented for leg raise. Similar to heel slide, repetition time was not quantitatively assessed by the clinician overseeing recovery. However, repetition time potentially provides insight to strength and power recovery, and is likely associated with pain and fatigue levels.

Relatively large peaks in knee joint angle did not always coincide with the start and end of a repetition based on hip angle, or there were multiple peaks within one repetition. Therefore, mean knee ROM (Figure 3.10) was found between positive and negative peaks in the knee joint angle trajectory rather than the ROM during the repetition as denoted by the hip movement. Knee ROM for the right and left legs were similar on day 2. On day 3, the largest difference between left and right knee ROM was observed, although the affected leg was still within 2 SD of the healthy leg. Finally, on day 6, knee ROM was similar on the right and left sides.

Quadriceps (or quad) lag is a commonly used term in clinic that characterizes quadriceps strength during leg raise, occurring when there is a lack of complete knee extension despite full contraction of the extensor muscles in the thigh. This was observed when the leg was moving through the motion even with maximal quadriceps activation, indicated by knee remaining in flexion through the motion. Extracting the actual angle at the maximum knee flexion point (Figure 3.11) and maximum extension point (Figure 3.12) could theoretically inform the clinician if the patient was reaching extension, and how far the knee is flexed/extended during the exercise. It is possible the knee does not reach full extension throughout the entire motion. Note positive knee angle was considered flexion and negative considered extension. Knee flexion showed similar trends as knee ROM with larger differences between the left and right leg. On all days, the affected leg had smaller maximum knee flexion angles. As the objective of the leg raise was to keep the knee fully extended throughout the motion, it was a positive indicator of recovery that the affected leg had a smaller knee flexion angle than the unaffected leg. This could be explained by more emphasis being placed on the affected leg during recovery. The mean extension angle (Figure 3.12) metric uses the opposite convention to flexion angle, with positive values indicating extension, and negative values indicate the knee was in flexion at the max extension. Magnitude of knee extension angle on the affected leg was greater than the unaffected leg on all days post-surgery.

Hip ROM in the sagittal plane, in Figure 3.13, was consistently smaller on the affected leg and outside the 95 % CI of the unaffected leg on day3 and 6 post-surgery. Sagittal plane hip ROM was 6.98°, 17.6°, and 10.6° smaller than the healthy leg on day 2, 3, and 6, respectively. Interestingly, sagittal plane ROM on day 365 was also 10.6° smaller on the right leg. While this finding may not be highly relevant for the APM procedure this case study focuses on; significantly lower hip sagittal ROM may indicate other imbalances or inability to maintain a straight leg at larger hip flexion angles.

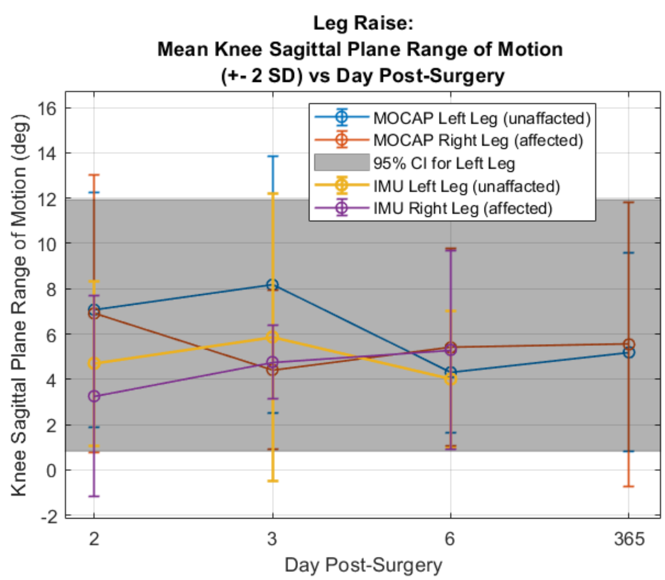

Figure 3.10: Average knee joint range of motion during leg raise on each day post-surgery (±2SD).

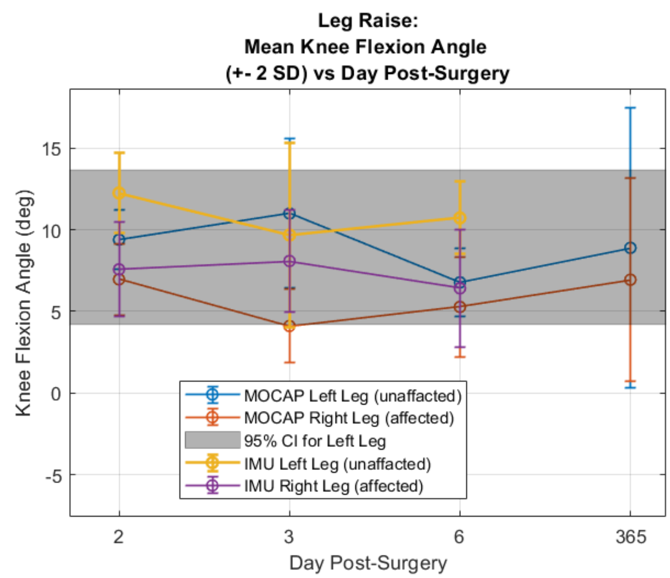

Figure 3.11: Mean knee flexion angle, for each day post-surgery, at point of maximum flexion during leg raise (±2SD).

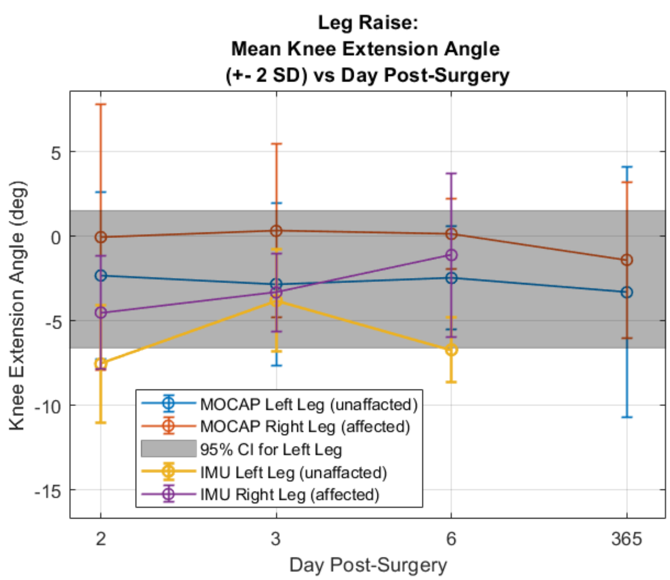

Figure 3.12: Mean knee extension angle, for each day post-surgery, at point of maximum extension during leg raise (±2SD).

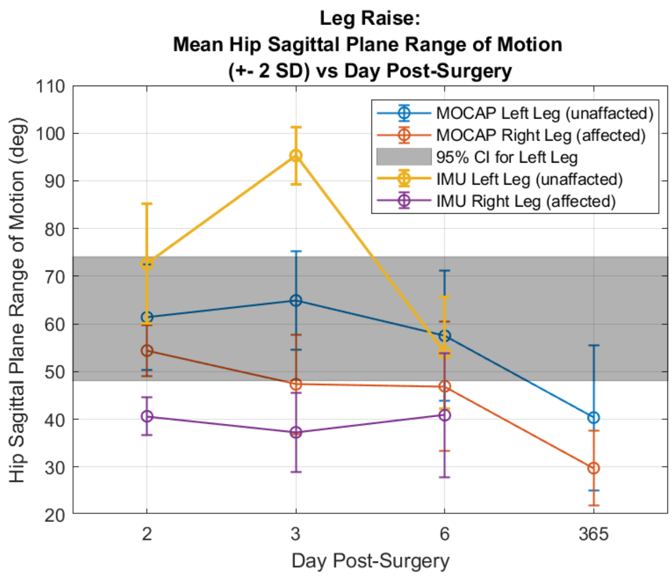

Figure 3.13: Sagittal plane (flexion/extension) hip range of motion for single leg raise on each day of recovery ($\pm$2SD).

3.4.2 Exploratory Measures

The leg raise exercise is difficult to assess purely based on kinematic measures. Another measure that is informally assessed in clinic and difficult to measure using kinematic data is muscle strength. Several potential recovery metrics were extracted from kinematic data to address these issues.

Time offset, measured as a difference in time between maximum hip flexion (midpoint of the exercise) and maximum knee flexion was taken as a potential indicator of quad lag. Figure 3.14 shows the time offset measured as the time between peak hip flexion and subsequent peak knee flexion. In the early days, a peak in knee flexion right after max hip flexion was observed. This pattern was predominant in earlier days compared to later days of recovery in the affected leg, as compared to unaffected leg. A positive value indicates maximum knee flexion occurs after the leg reaches the highest point, and reversing back down to the floor. Negative values indicate maximum knee flexion occurs before the leg reaches the highest point. In comparison, time offset tended to be closer to zero (simultaneous peak flexion of the hip and knee) in the unaffected leg on all days of recovery. For the affected leg, offset was positive on all days of recovery, tending to increasing from day to 2 to day 6, indicating that the max knee flexion occurred even later in the exercise. Consistent late maximum flexion could suggest a potential weakness in quadriceps extensor strength while the hip was being extended and lowered to the ground. All values for the affected leg were within the 95% CI for the unaffected leg although a significant difference was observed between limbs on day 2 and not day 6, which may show a meaningful difference between limbs that decreases as recovery progresses.

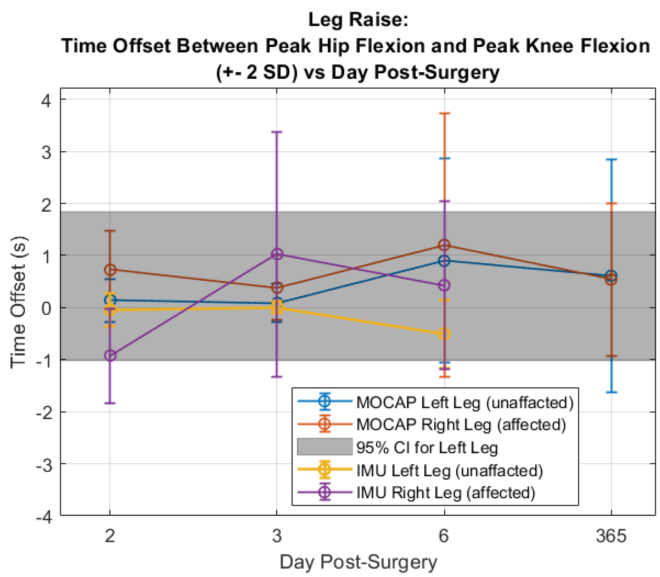

Figure 3.14: Mean time offset, measured as the difference between time of maximum knee flexion and time of maximum hip flexion, for each day of recovery post-surgery (±2SD).

RMS angular velocity, RMS angular acceleration, and RMS angular jerk were all extracted for the knee joint. Angular velocity and acceleration were moved to A for brevity. Considering the instructions is to keep the knee straight during leg raise, lower angular rates of motion in the knee joint are desired. Jerk, the time derivative of acceleration, has been suggested as a measure of smoothness in physical movement. Smoothness is one of the verbal cues used by clinicians during the leg raise, and visually assessed during later stages of recovery. RMS angular jerk for the knee is shown in Figure 3.15, where a smaller jerk corresponds to a smoother motion. On day 2 post-procedure, mean angular jerk was $177°/s^3$ greater on the affected leg compared to the unaffected leg. This relationship changes on day 3 and day 6, when mean jerk was $771°/s^3$ and $775°/s^3$ lower in the affected knee compared to the unaffected knee. Average jerk was similar between affected and unaffected limbs one year post-surgery and both right and left knee jerk measurements were smaller one year post-surgery compared to recovery days.

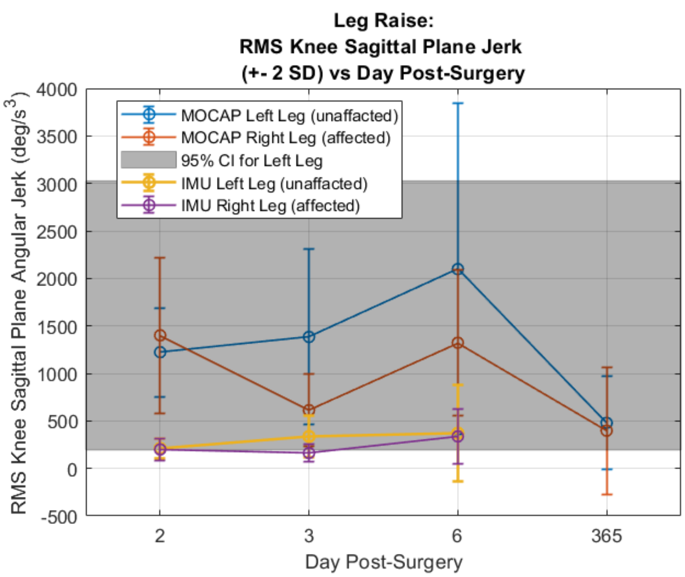

Figure 3.15: Knee RMS angular jerk on each day of recovery for the leg raise (±2SD).

A trend was observed in the affected limb sagittal plane knee joint angle during the leg raise, where the knee joint became further in flexion as the subject performed more repetitions. A linear best fit line for the sagittal knee angle was used to quantify this trend. Table 3.4 shows the slope values for the best fit lines. The unaffected leg on day 2 and 3 have positive slope values, whereas the slope on day 2 and 3 for the affected limb is negative. On day 6 the slope of the best fit line for the affected limb is positive, indicating that the knee flexion-extension angle stays the same or moves more towards extension as the subject performed more repetitions.

Table 3.4: Slope Values of Linear Best Fit Line for Sagittal Plane Knee Angle

	Unaffected Leg	Affected Leg
Day 2	0.043	-0.056
Day 3	0.022	-0.153
Day 6	-0.064	0.004

Other exploratory metrics assessed for the leg raise were: up-down time ratio, maximum angular deviation during each repetition, and normalized time of maximum angular deviation. These metrics either did not show clear discernible trends in recovery or did not show trends that were not already demonstrated in presented metrics. Time ratio and time of maximum knee angular deviation did not show recovery trends in terms of significant improvement over time or between limbs. Maximum knee angular deviation showed the same trends as knee sagittal plane range of motion, an existing metric. Plots showing the data from these metrics were included in Appendix A.

3.4.3 Supine Straight Single Leg Raise Discussion

Table 3.5 below lists the p-values for each t-test for the leg raise recovery metrics. Knee joint ROM showed no statistically significant differences between limbs or rehab days. Although knee range of motion was expected to decrease, the goal of the exercise is to maintain a straight knee the entire time, making knee ROM small and any variability large in comparison to the values measured. Knee extension angle showed a difference between the affected and unaffected legs on day 6 only and extension angle did not show a significant change on the affected leg over recovery. Knee extension angle was also greater on the affected side than the unaffected side, so any statistical difference was in favor of the affected leg, indicating the affected leg performed better. Knee flexion angle, which was greater on the unaffected leg actually shows a significant difference between the affected and unaffected legs on day 2 and on day 6. Where the desired was a low flexion angle, these tests were showing that the unaffected leg might be significantly worse than the affected leg in this metric. This unexpected trend could be explained by more emphasis being placed on the affected leg during recovery.

Hip ROM showed significant differences between the affected and unaffected legs, and between the affected leg on different days. Hip ROM was not considered an important factor in satisfactory performance of this exercise, other than the leg should be raised to approximately 45° flexion. During recovery the athletic therapist did not make any adjustments to the hip movement during therapy sessions. While hip flexion was not considered a typical metric in APM recovery, sagittal plane ROM was significantly smaller on the affected leg compared to the unaffected leg. Determining meaningful conclusions from significance tests for hip ROM metrics during leg raise would require professional interpretation.

There was no significant difference in knee RMS jerk between legs on day 2, however jerk tended to be higher on the affected leg compared to the unaffected leg. After day 2, jerk was higher on the unaffected leg and on day 6 jerk in the unaffected leg was significantly larger. This is contrary to the expectation that the healthy leg is stronger and smoother when performing the motion, however possibly indicates that there was no deficit in the affected limb. Jerk also followed trends in fatigue ratings over recovery in the affected leg,

Table 3.5: Unpaired T-test P-Values for Single Straight Leg Raise, Between Affected Leg Over Recovery and Between Affected and Unaffected Legs

	Affected vs Unaffected Leg		Affected Leg	
	Day 2	Day 6	Day 2 vs Day 6	Day 6 vs Day 365
ROM	0.925	0.254	0.342	0.925
Extension	0.271	0.002	0.904	0.129
Flexion	0.003	0.044	0.063	0.221
Hip ROM	0.031	0.005	0.036	<0.001
Hip Abd/Add	0.002	<0.001	0.132	<0.001
Hip Rotation	0.032	0.136	0.022	0.597
Max Knee Angle	0.093	0.006	0.974	0.020
Time of Max Angle	0.923	0.014	0.379	0.970
RMS Angular Velocity	0.130	0.104	0.888	0.533
RMS Angular Acceleration	0.830	0.062	0.786	0.036
RMS Jerk	0.390	0.022	0.723	<0.001
Repetition Time	0.007	0.344	0.002	<0.001
Extension/Flexion Time Ratio	0.378	0.244	0.411	0.791
Time Offset	0.009	0.584	0.431	0.207

where jerk increased on days when fatigue was rated higher (6/10) and decreased on days fatigue was rated lower (0-2/10). Knee joint angular jerk does not provide good indication of recovery for this case study during the leg raise exercise, however may be linked to fatigue in the affected leg during recovery. There were also significant decreases in knee joint RMS angular jerk on the affected leg between day 6 and day 365. This finding, paired with the drop in magnitude for both right and left legs, and negligible difference between the the legs on day 365 may indicate that both legs were performing similarly during recovery.

Time offset between the exercise midpoint and max flexion of the knee was significantly larger on the affected leg compared the unaffected leg only on the second day post-surgery. This was also the day with the largest magnitude difference between the right and left legs. After day 2 the difference between the legs decreases, which might show evidence that this might be able to be used as a possible recovery metric. Further professional feedback regarding the reason for this occurrence and further testing on more subjects undergoing similar recovery would provide concrete evidence that this metric measured a clinically important finding.

3.5 Straight Line Over-Ground Walking

The main goal of the second phase of rehabilitation was to recover a normal walking pattern and walking without a limp. Definition of normal walking patterns will vary by therapist and patient. In this case study, unaffected leg and one year post-op measures were considered as proxy measures for normal gait. The subject walked with axillary crutches, weight bearing as tolerated for the first few days after the procedure. Subject progressed to full weight bearing walking in every day life after two days post-surgery. Straight line walking was evaluated in rehab as an indicator of functional recovery after lower limb surgery, collected on day 2, 3, and 6 post-surgery. At day 6, the subject had been walking for 4 days without crutches. Normal and dysfunctional walking patterns are highly varied across subjects, as are the cause and type of dysfunction. Structural damage may cause an abnormal gait pattern, however, pain or stiffness are just as likely to cause disruptions in gait [63]. In this case study, the subject underwent a localized knee surgery and was otherwise healthy. Dysfunction is primarily expected in the knee joint because of structural changes and pain post-procedure. Walking was assessed to ensure there was no lingering negative effects, however, walking was not a main concern for the therapist. Table 3.6 contains the pain and fatigue scores for the walking collections.

Table 3.6: Pain and Fatigue Scores Recorded During Straight Line Overground Walking

	Day 2		Day 3		Day 6	
	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue
Walking 1	2	2	0	0	0	0
Walking 2	2	2	2	0	0	0

The scores remained relatively low throughout recovery, day 2 had the highest pain and fatigue scores of 2/10. On day 3 pain was ranked 2/10 for one of the collections an otherwise all other scores were 0/10. The patient was pain free with simple straight line walking quickly after surgery, supported by the discontinued use of crutches.

3.5.1 Range of Motion Recovery Metrics

Part of gait recovery involves recovery of normal joint range of motion. Since joint range of motion during gait is highly variable person to person, normative ranges can only provide a general baseline. Instead joint range of motion can be compared to the range of motion on the unaffected leg and one year post-surgery. Although this may be a better comparison than normative data, gait patterns can also be highly variable in the same subject depending on the day [64]. Joint ROM for the individual legs during swing phase were averaged separately for each day.

Hip sagittal plane ROM was plotted in Figure 3.16. Blue and yellow lines refer to the motion capture-measured joint ROM for the right and left legs, respectively. The red and purple lines are the same metrics measured using the sensor-based approach. Average hip ROM on the affected leg was slightly lower than hip ROM on the unaffected leg, although all days the affected leg measurements were within two standard deviations of the average for the unaffected leg. Average hip flexion-extension ROM for the affected leg increased from 33.5° on day 2 to 38.2° on day 6. The difference between the unaffected and affected legs stayed fairly consistent across recovery at 2.18° on day 2, 0.598° on day 3, and 2.20° on day 6. One year post-operation hip ROM increased only slightly to 29.9° on the right leg and 44.4° on the left leg. The right leg hip ROM was slightly smaller than published reference values of 46.2° of flexion-extension ROM for the hip during normal gait [65], while the unaffected hip was closer to normative range on day 6 and one year later.

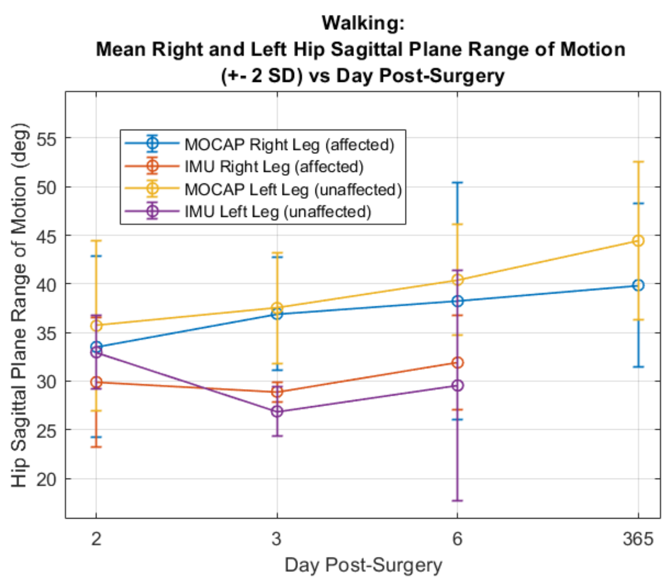

Figure 3.16: Hip sagittal plane range of motion averages for overground walking for motion capture and sensor modalities (±2SD).

Average knee ROM in the sagittal plane is plotted Figure 3.17 for both legs during swing phase. The affected knee ROM is 2.95° smaller than the left leg on the second day of rehab (55.4°) and 1.99° and 2.78° larger than the left leg on day 3 and day 6. Knee angle reaches the normative range of knee sagittal plane motion of 63.6° [65], between day 3 and day 6.

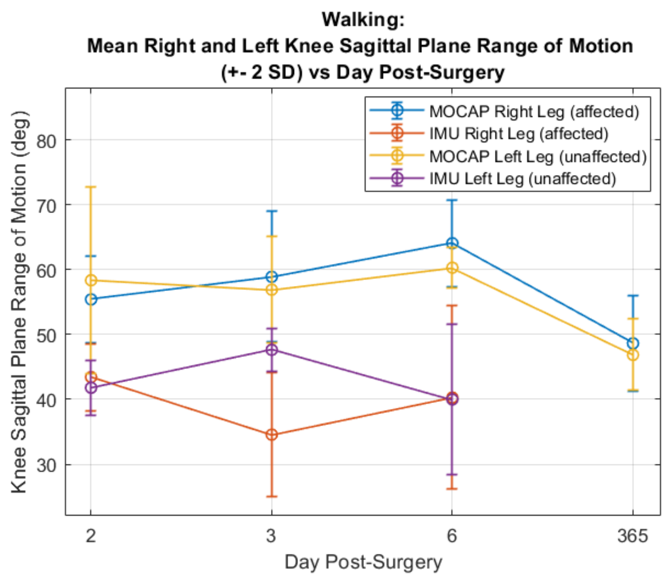

Figure 3.17: Knee sagittal plane range of motion averages for overground walking for motion capture and sensor modalities (±2SD).

3.5.2 Gait Feature Recovery Metrics

Although the lower limb joint ROM was in the functional range and comparable between left and right legs, the subject was walking with a limp the first few days after the surgery. Antalgic gait, commonly referred to as walking with a limp is characterized by spending more time on one leg compared to another, often to avoid spending time in stance phase on the limb experiencing pain [63]. Alternatively, if there is an injury or cause of instability in a lower limb, an individual may feel less stable or comfortable on one leg versus the other and spend more time on the other leg. Gait characteristics, such as step time, step length, and step width provide insight on how gait changed for the case study patient.

Figure 3.18 shows the right vs left leg step time during overground walking on day 2, 3 and 6 post-surgery and one year after. Affected leg step time was lower than the unaffected step time on all days of recovery. Based on the antalgic gait model, the affected leg would have greater step times than the unaffected due to discomfort associated with the procedure. Greater time spent in swing phase of gait means less time the painful limb is weight bearing. However, pain scores for walking were rated low: 2/10 on the pain scale, even on day 2, after which scores decreased to 0/10. The low pain scores provide insight on why the patient actually spent more time on the affected leg compared to the unaffected leg.

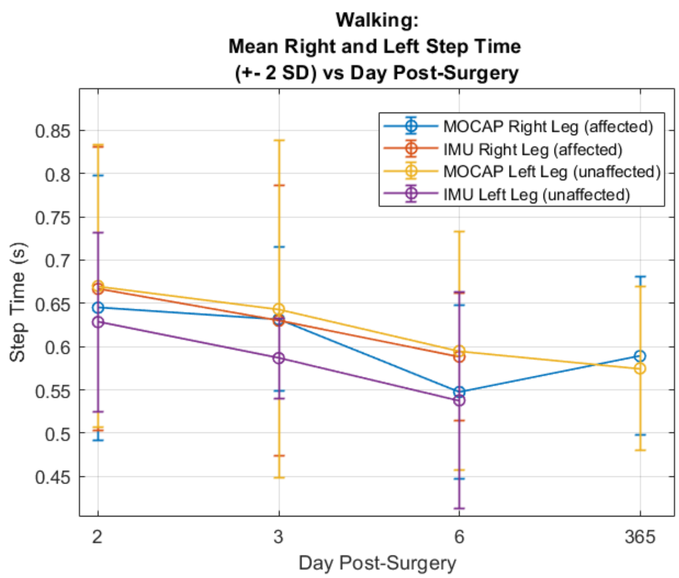

Figure 3.18: Mean step time of the affected leg compared to the unaffected leg during rehabilitation, for overground straight line walking (±2SD).

More information is available in Figure 3.19, which plots of average step lengths for the right and left legs. Right step length is on average 0.039 m shorter than the left step length on day 2 and 0.0045 m shorter on day 3 post surgery. Smaller step lengths on one limb contribute to a limping gait pattern and could be used to assess a limping gait remotely. The difference on day 3 is negligible and right step length is 0.012 m longer on day 6. Step length on both legs also increases from day 2 to day 6 of recovery by 0.069 m on the right leg and 0.018 m on the left leg. The smaller step time on the affected side is likely associated with the smaller step length on the affected side. If the limb is also moving slowly, step time will be smaller for a shorter step length. Shorter step length on the injured leg is also explained by instability in the limb to bear loads that occur further beyond the base of support. Although this pattern increases the amount of time spent on the affected leg, instability due to larger step lengths is avoided. This gait pattern may have been an alternate method to avoid pain and force through the affected limb.

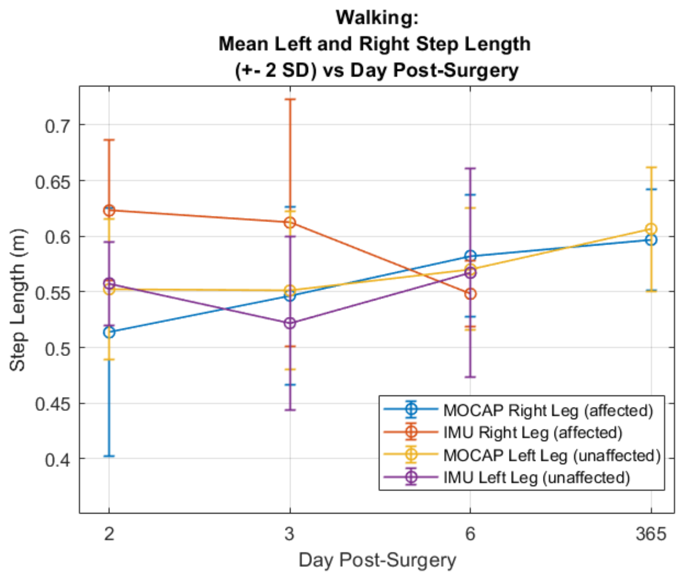

Figure 3.19: Mean step length of the affected leg compared to the unaffected leg during rehabilitation, for overground straight line walking (±2SD).

Instability can manifest in gait by the widening of step width. A wider step width creates a larger base of support when walking, providing more stability when walking. Step width for the motion capture data is presented in Figure 3.20. Step width was taken as the distance between the left and right feet perpendicular to the direction of travel. On day 2, the mean affected step width was 0.058 m wider than the unaffected side, showing a tendency to widen the base of support when the affected leg was leading the gait cycle. After day 2, the affected leg step width was smaller than the step width on the unaffected limb. This trend was also seen in the data from one year post-surgery, where right step width was smaller than the left step width. Step width data could potentially indicate improvement in stability and return of a normal gait pattern.

After a unilateral procedure, asymmetry index is a useful tool to detect gait pattern differences between the affected and unaffected legs. The absolute value of the mean asymmetry index, for step length and step width on each day of recovery, is presented in Figure 3.21. Asymmetry index was calculated using mean step length or width for all steps in each therapy session. As such, standard deviations were not presented for these metrics. From Day 2 to 6, step length asymmetry index decreased by 70.3% and step width asymmetry index decreased by 32.4%. Step length and width asymmetry between day 6 post-surgery and one year later only had small differences of 0.471% and 2.46%.

3.5.3 Over-Ground Walking Discussion

Plotted data in Section 3.4.1 show small differences in joint ROM bilaterally and between days of recovery. Walking requires a functional level of knee joint motion (25°), which is small compared to knee ROM assessed in heel slide (>80°). As expected, there were no significant differences between the affected and unaffected legs or on the affected leg between day 6 and 365 for the hip sagittal or frontal plane motion.

Range of knee sagittal plane movement showed a significant difference between day 6 and day 365 on the affected leg, again this could be due to multiple factors or demonstrate intra-subject variability. The knee joint also demonstrated significant difference between the affected and unaffected legs on day 6; however, the affected leg ROM was greater than the unaffected leg. Perhaps more clinically valuable was the significant increase in knee ROM on the affected leg between day 2 and day 6 post-surgery. Unlike targeted knee ROM exercises, walking was a whole body functional therapy exercise where there was not a specific joint-based recovery goal. Clinically, this significant increase in knee joint

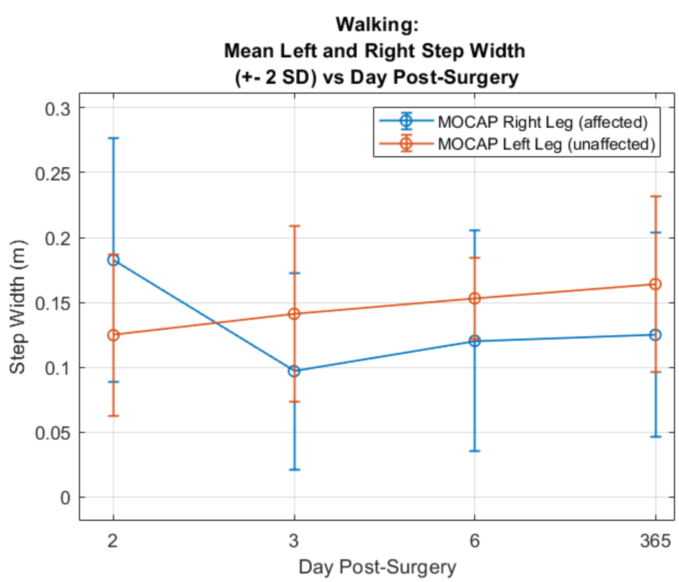

Figure 3.20: Mean step width of the affected leg compared to the unaffected leg during rehabilitation, for overground straight line walking (±2SD).

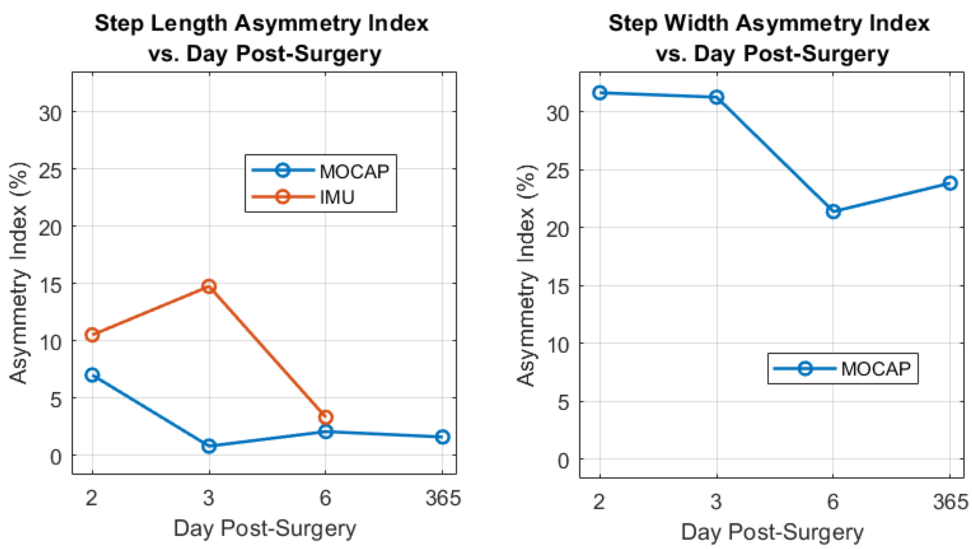

Figure 3.21: Mean step length and step width asymmetry index between affected and unaffected legs for overground walking.

ROM, well within the maximal range of knee flexion and extension, could demonstrate improvement to normal gait patterns and normal functional ROM in the affected joint.

Step time had significant difference on the affected leg between day 2 and 6 only, decreasing by 0.098 s over the recovery period. While not tested for statistical significance, step time on the unaffected side also decreased during rehabilitation by 0.075 s. Step length on the affected side also showed a significant increase from day 2 to 6 by 13.4%. A steady decrease in step length variability on the affected side was observed day 2 to day 6. Increased step length and decreased step time indicate increased gait speed, which shows the subject became more comfortable accepting higher ground reaction forces on the affected leg at heel strike [66]. Considering pain is often the cause of limping during walking, daily pain scores correspond to the improvement of gait characteristics over time. Significant step time decreases and length increases on the affected side, decreasing disparity between the left and right legs, indicate faster gait speeds and a strong indicator of limp improving over the recovery period.

Step width is a good indicator of gait stability, where a wider step width indicates a cautious gait pattern to maximize stability. Average step width in healthy individuals is 3 to 8 cm [67]. On day 2, step width on the affected side was 18.3 cm. Step width for the affected leg decreased significantly between day 2 and 6 to 12.0 cm. Step width on the affected leg was also significantly larger than the unaffected leg on day 2. No significant

Table 3.7: P-Values for Unpaired T-tests for Overground Walking, Between Affected Leg Over Recovery and Between Affected and Unaffected Legs

	Affected vs Unaffected Leg		Affected Leg	
	Day 2	Day 6	Day 2 vs Day 6	Day 6 vs Day 365
Hip ROM	0.163	0.478	0.109	0.407
Hip Abd/Add	0.647	0.184	0.024	0.750
Ankle ROM	0.109	0.969	0.880	<0.001
Knee ROM	0.243	0.047	0.004	<0.001
Step Time	0.467	0.217	0.015	0.271
Step Length	0.093	0.484	0.010	0.001
Step Width	0.006	0.140	0.021	0.074

difference between legs were observed on day 6. Although step width does not decrease to normative values, both legs on day 365 are also greater than the upper limit of the normative range. More important clinically could be the improvement in step width on the affected leg indicating improved stability and return to comfortable gait patterns.

For the best estimate of gait asymmetry with limited data points, the average of the left and right steps were used in the gait asymmetry equation for each day. As such, statistical testing was infeasible for step length and step width asymmetry. Both step length and step width asymmetry decrease over the recovery period. Additionally, asymmetry indices are similar one year post surgery and the last day walking was collected. Although all efforts were made to provide a good comparison, a larger sample size would improve the estimation of gait asymmetry and the clinical value of the results. In practice, subjects could walk in longer bouts and more frequently to get into a rhythmic gait and have a larger sample size for comparing means and determining significant changes.

3.6 Double Leg Goblet Squat

The athletic therapist overseeing rehabilitation cleared the case study subject to progress to phase C on day 7 post-surgery. Exercises progressed to closed chain and single leg weighted exercises, introduced in stages leading up to final progression of the exercise. The double leg goblet squat is demonstrated by the illustration in Figure 3.22 below [68]. The initial position is shown on the left, standing with both feet on the ground shoulder width apart holding a weight at their chest. The exercise is done by moving to the bottom position, shown on the right, and then back to the initial position.

Figure 3.22: Illustration of the double leg goblet squat exercise. The initial position on the left and the bottom position on the right.

Before the full squat exercise was added to the exercise protocol, quarter and 90° knee flexion squats were done on day 3 and day 6. Both intermediate squats were the same squatting motion, but stopped at 45° and 90° knee flexion. These intermediate exercises were not analyzed, as they were only performed on single days leading to full squats. Two sets of double leg goblet squats were done on each day of phase C, day 7, day 9, and day 15. Both pain and fatigue, listed in Table 3.8, were rated a 2/10 for both sets on day 7. Pain scores were similar on day 9 at 2/10 and 3/10 for the second set, with fatigue rated 0/10. On the last day, pain and fatigue were both rated 0/10. The pain and fatigue scores were quite low during phase C, at this point it had been over a week post-surgery and after effective pain management the subject was performing weighted double support exercises with minimal pain.

Table 3.8: Pain and Fatigue Scores Recorded During Squat

	Day 7		Day 9		Day 15	
	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue
Squat 1	2	2	2	0	0	0
Squat 2	2	2	3	0	0	0

3.6.1 Recovery Metrics for the Double Leg Goblet Squat

The goblet squat is a close chain kinetic exercise important in assessing recovery from a multitude of disorders and injuries. Squats are often used to assess strength and to assess joint ROM in a functional movement [69]. It is a complex motion including simultaneous hip flexion, knee flexion, and ankle dorsiflexion [70]. Because the squat is a multi-joint exercise, there are different theories on which joint plays the largest role in the motion. It is suggested that of the two major joints involved in the exercise, the hip joint should provide the driving force in the exercise [71] and can help unload the knee in the sagittal plane by decreasing the quadriceps force necessary to perform the action [72]. Another group theorizes that to perform the double leg squat efficiently, it is important to have ankle and hip mobility along with foot and knee stability [73]. The importance of ankle mobility during squat is supported by Gawdra et al., as well as the impact of ankle mobility on knee stability in the frontal plane [69]. From a kinematics perspective, common mistakes when performing the squat exercise include knee valgus or varus during the downward phase of the movement, described as the knees coming together or apart excessively, or excessive hip flexion during the entire squat exercise [46].

Joint ROM in sagittal plane of the knee joint was assessed in Figure 3.23 for each day of recovery. As a double leg exercise, one limb is generally forced to accommodate the deficit in the other limb otherwise the motion would be unbalanced. The right (blue line) and left (yellow line) legs follow the same trend from day 7 to day 15. The affected leg knee ROM increased from 111° to 119 ° over the second week of recovery. One year-post-surgery, the affected leg knee ROM was 142°, 23° larger than when the subject was cleared to return to sport. High performance sport requires a higher level of rehabilitation than return to normal functional movement. Knee ROM during the squat at day 15 was outside of 2 SD of mean knee ROM one year post-op. If this data, or a similar reference baseline before surgery, was available to the clinician during rehabilitation the patient may not have been cleared to return to sport. Either the subject did not feel comfortable reaching that degree of knee flexion, the leg/knee was not strong enough to extend from that deep of a squat, and/or the knee was physically incapable of reaching the ROM because of persisting control and/or structural issues. While this data cannot diagnose the cause, it can inform clinician decision-making and identify potential problem areas.

Mean hip ROM in the sagittal plane stayed within range of ± 2 standard deviations for the first recovery day goblet squat was in the protocol. Right hip ROM increased from 115°on day 7 to 121 °on day 15. Being a closed chain exercise it follows that the hip ROM along with the knee range measurement one year post-op was also outside the range reached during recovery.

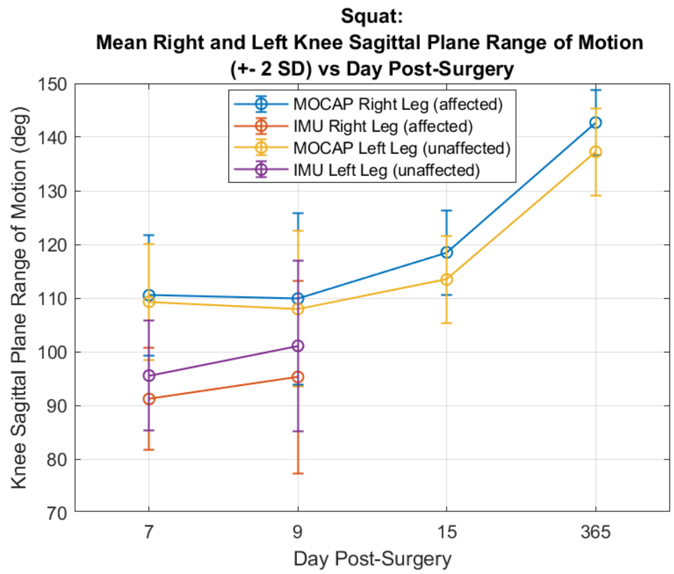

Figure 3.23: Mean knee range of motion in the sagittal plane during double leg goblet squat over phase C of recovery (±2SD).

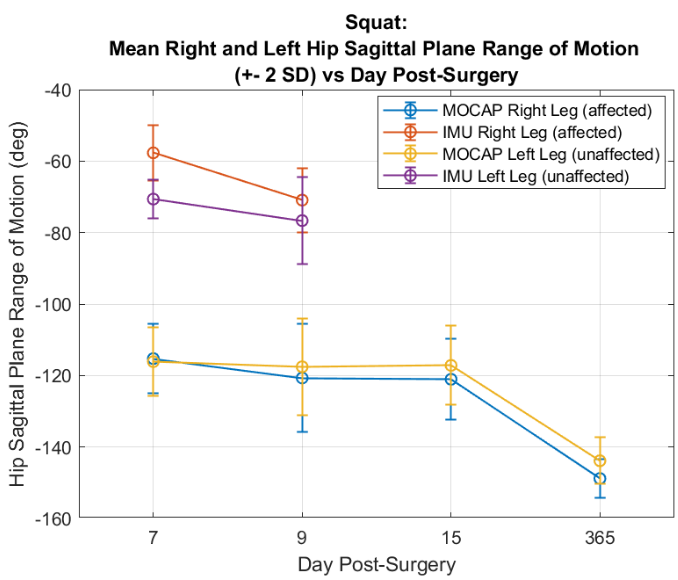

Figure 3.24: Mean hip sagittal plane range of motion during double leg goblet squat (±2SD).

When moving downward into the bottom position of the squat, angling the knees inward or outward would be evident in hip frontal plane ROM, or hip abduction-adduction, shown in Figure 3.25. Negative values indicates adduction (inward) and positive value indicates abduction (outward). During the squat, the knees should be pointed slightly outward or have a varus angle. Hip frontal plane ROM on both legs stays consistent around 12.4°with similar variability on each day of the recovery period and one year post-surgery. There is a slight increasing in the difference between the left and right limbs as recovery progresses. When standing upright, changes in hip transverse plane of motion would indicate valgus or varus angling of the knees. For brevity, hip external-internal rotation plots are shown in Appendix B and not discussed further in this chapter.

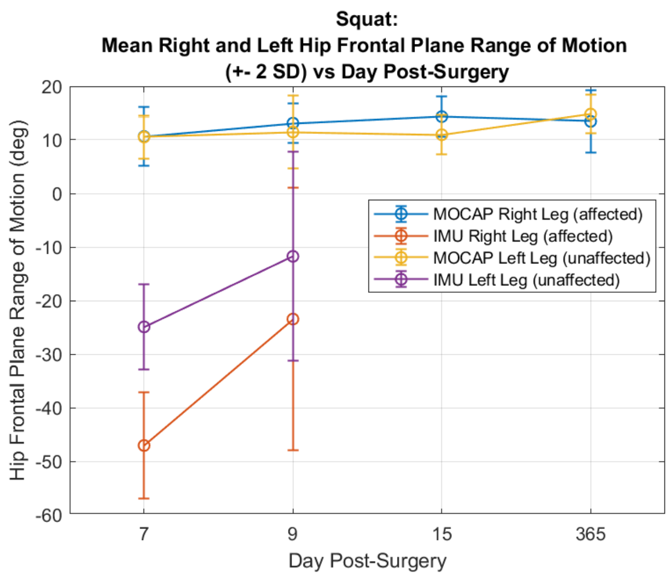

Figure 3.25: Mean hip frontal plane range of motion during double leg goblet squat (±2SD).

Essential for squatting, the ankle joint is the final link in the chain. Figure 3.26 shows mean ankle ROM on each day, where negative values indicates a larger ROM in dorsiflexion. Ankle ROM on the unaffected side varied at most 1.13°between days. On the affected side, ankle ROM increased over recovery and then decreased one year post-surgery to a similar value at the start of recovery and to the unaffected side. Given an increase in knee ROM of 8° over the recovery period, there is a corresponding increase of 5.17° ankle ROM between day 7 and 15. The increase in hip and ankle ROM one year post-op and decrease in ankle ROM indicates the subject is reaching a deeper squat and relying on the hip and knee more than the ankle.

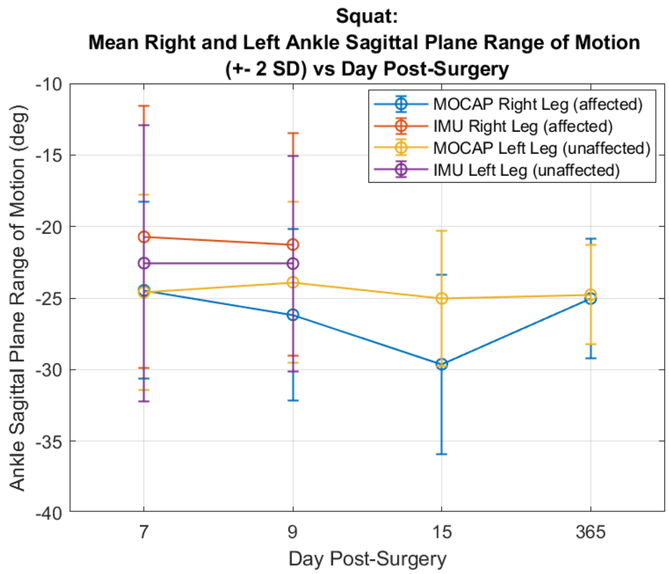

Figure 3.26: Mean ankle sagittal plane range of motion during double leg goblet squat (±2SD).

3.6.2 Exploratory Measures

In phase C, most of the exercises are centered around recovering strength and proprioception in the affected joint. While measuring strength using a purely kinematics-based tool is challenging, knee joint RMS velocity may provide a proxy measure of knee strength by showing that subject can move the same (body) weight more quickly. Figure 3.27 shows knee angular velocity over the recovery period. From day 7 to 15, knee angular velocity increased by $40.8°/s$ on the affected side ($103.9°/s$ to $144.6°/s$) and similarly on the unaffected side ($100.8°/s$ to $135.5°/s$). On day 365, RMS angular velocity was similar to end of rehab values at $134°/s$, $31°/s$ higher than at the start of phase C. Considering the progression observed, velocity during a strength exercise could inform strength recovery from purely a kinematic based metric.

Repetition time and extension to flexion time ratio were also extracted for the goblet squat exercise (plots in B). Repetition time decreased steadily over recovery from $2.72s$ to $2.03s$ on day 15. However one year post-surgery repetition time increased to $2.57s$. The time ratio, or the time between rising from and entering into the squat stays consistently around 0.8 on all collection days including day 365. RMS angular velocity and repetition time were better potential indicators of recovery compared to time ratio.

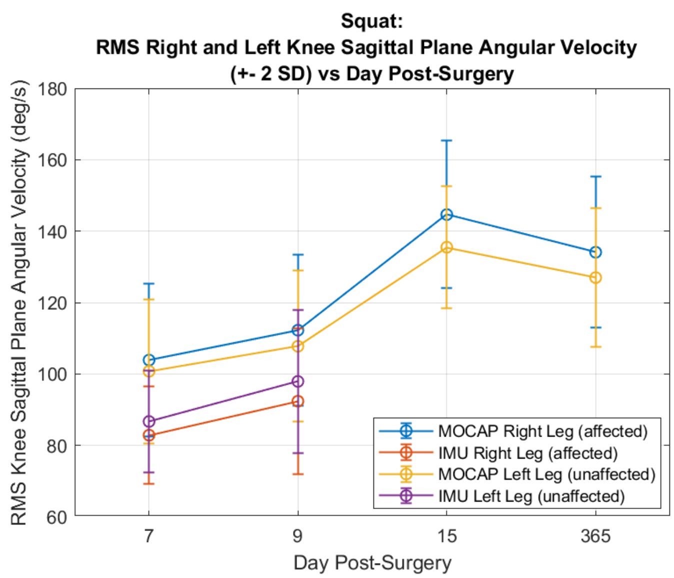

Figure 3.27: Mean knee sagittal plane RMS angular velocity during double leg goblet squat ($\pm$2SD).

3.6.3 Double Leg Goblet Squat Discussion

Table 3.9 shows p-values for unpaired t-test results for the goblet squat exercise. There was a significant increase in hip ROM in the sagittal and frontal planes on the affected leg from day 7 to 15. Physically a change of 3.71°in hip frontal plane angle may not be clinically relevant. The 5.78° change in hip flexion-extension angle is larger, although there is a more significant increase of 27.8° from the end of recovery to one year post-surgery. It is useful to have confirmation that there was an increase in hip flexion over recovery as a 5.78° angular increase would be difficult to detect visually. The disparity in the depth of the squat between one year post and the end of recovery may indicate that full ROM was not recovered at the end of rehab.

Knee valgus refers to the inward collapse of the knees usually when the hip is flexed, characterized by hip adduction and internal rotation. Knee valgus angle during squat is a highly correlated to knee pain [74], [75] and a common performance error during squat [69]. It is also linked to insufficient abductor strength and can lead to different co-morbidities [76]. Hip adduction-abduction ROM is an indicator of knee valgus angle, where a negative value indicates adduction and a positive value indicates abduction (Figure 3.25). Hip abduction-adduction was also statistically significantly different between the affected and unaffected legs on day 15 post-surgery, though the physical difference was only 3.38°. The difference between the affected and unaffected legs increases as recovery progressed. It is possible that as the squat increased in depth the hip abduction-adduction angle does not stay symmetric between limbs. However, both legs remain in abduction across recovery days and do not decrease, indicating the knee would remain in the desired knee varus position (or knee outward position).

Ankle sagittal plane ROM on the affected leg is significantly greater on day 15 compared to day 7. Ankle mobility is essential for squat performance [73] and the increase in the affected leg over recovery is an example of how mobility increases as squat depth increases. There was also a significant difference between affected and unaffected limbs on day 15 and a significant decrease in the affected leg between day 15 and one year post-surgery, while the unaffected leg stays consistently around 25° flexion (Figure 3.26). Clinical feedback on these trends in sagittal plane ankle range, compared to the steady trend on the unaffected side would provide more insight on the factors behind this phenomenon. Knee sagittal plane angle showed a significant increase over the recovery phase and between day 15 and day 365, on the affected leg and most likely on the unaffected leg as well. No significant differences were found between the affected and unaffected limbs. As discussed when looking at the magnitude of the difference between recovery and one year post-surgery, this information or a baseline before recovery would be beneficial to have when providing therapy to patients, especially when treating the patient to optimal recovery.

Table 3.9: P-Values for Unpaired T-tests for Goblet Squats, for the Affected Leg Between Recovery Days and Between Affected and Unaffected Legs

	Affected vs Unaffected Leg		Affected Leg	
	Day 7	Day 15	Day 7 vs Day 15	Day 15 vs Day 365
Hip ROM	0.653	0.148	0.019	<0.001
Hip Abd/Add	0.859	0.002	<0.001	0.465
Hip Rotation	0.003	<0.001	<0.001	<0.001
Ankle ROM	0.745	0.006	<0.001	0.002
Knee ROM	0.200	0.045	<0.001	<0.001
Knee RMS Angular Velocity	0.252	0.004	<0.001	<0.001
Time Ratio			0.110	0.855
Repetition Time			<0.001	<0.001

RMS angular velocity for the knee joint showed significant change in the affected leg between day 7 and day 15 and also between day 15 and day 365. This result provides further evidence of important change in this metric over the recovery period and further supports the potential to be used to track recovery. Time ratio did not show significant change over recovery or between recovery and one year later. The decrease in repetition time over recovery was statistically significant, as well as the change between end of recovery and on year post-surgery (Appendix B). The significant increase in repetition time over recovery may correspond to increased comfort with the exercise and be linked to decreasing pain levels.

3.7 Single Leg Romanian Dead Lift

The single leg Romanian deadlift (RDL) was prescribed during phase C of rehabilitation as part of recovery strength and stability. The RDL exercise starting position is shown on the left in Figure 3.28. Standing on one leg with a straight (but not locked) knee, the other leg (referred to as the moving leg here) is moved backwards by hinging forward at the hip, keeping the moving leg straight. The final position is shown in the right of Figure 3.28 [77].

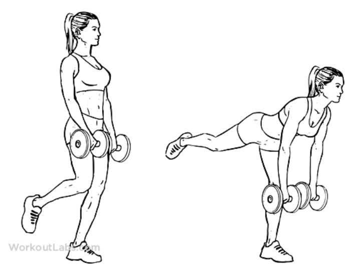

Figure 3.28: Illustration of the Romanian deadlift exercise, the beginning on the left and the final position on the right.

Cues for this exercise to be performed successfully were maintaining balance, keeping the stationary and moving legs straight, the torso and moving leg being perpendicular to the ground, and keeping the hips level and perpendicular to the ground. The RDL was performed without weight on day 3 and day 6 post-surgery, after which therapy progressed and weight was added to the exercise on days 7, 9 and 15. The unweighted RDL was performed on day 3 with the approval of the clinician monitoring recovery. This is an example of the case study rehab progressing quicker than general timelines prescribed.

Pain and fatigue scores for the RDL, listed in Table 3.10, were 3/10 for the affected limb on day 3, but decreased to 0/10 on day 6. Pain increased to 5/10 on day 7 and 2/10 day 9. Weight was added on day 7 which aligns with increased pain scores.

Table 3.10: Pain and Fatigue Scores Recorded During Single Leg Romanian Deadlift

	Day 3		Day 6		Day 7		Day 9		Day 15	
	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue	Pain	Fatigue
RDL Right Leg	3	4	0	7	5	5	2	5	0	0
RDL Left Leg	0	0	0	4	1	3	1	2	0	0

3.7.1 Recovery Metrics

Recovery metrics were mainly assessed visually for control and strength while performing the exercise. Considering the exercise is a multi-joint movement, interpreting kinematic results in any single joint in isolation as a recovery metric is challenging. ROM in joints of the moving and stationary legs were analyzed for potential recovery patterns. RDLs were performed standing on the right leg, which were labelled as right leg down in the figure legends, and similarly labelled for the left leg. ROM metrics were plotted separately for the moving and stationary legs. The blue and red lines are the motion capture metrics represent right and left leg down, respectively, with yellow and purple plots corresponding to sensor-based metric data.

Range of motion of the moving hip in the sagittal plane was plotted in Figure 3.29. Ideally, the moving leg moves with or stays in line with the torso as the leg moves to the final position at least 90 ° to the stationary leg (i.e., perpendicular to the ground). The torso is moved to the same position in front of the stationary leg. The ROM of the moving hip was around zero on day 3 for left leg down and positive on day 3 for the right leg down, indicating that the hip was slightly flexed. When standing on the affected leg, the moving hip stayed in slight flexion (compared to zero or negative ROM showing extension past 90°), potentially indicating lack of strength or stability to reach the final position of the RDL. For the first few days this exercise was completed, the moving leg hip was on average 5.00° more in extension than when the affected leg is standing when the unaffected leg was down. Both the left and right leg ROM decreased over recovery and progressed to a mean negative hip ROM, indicating that both the affected and unaffected leg hips are in extension at the final position. The difference between the affected and unaffected legs decreases to 2.59° on day 9 and 0.736° day 15, showing the symmetry between legs increasing as the patient progresses through therapy.

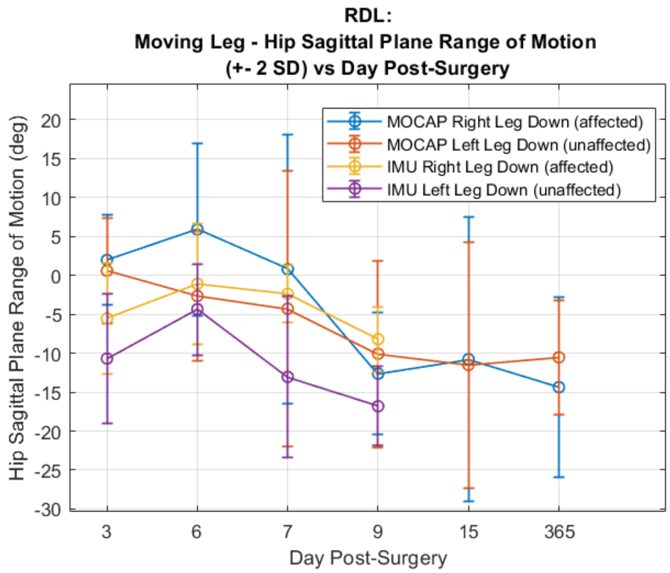

Figure 3.29: Mean moving leg, hip sagittal plane range of motion during the single leg Romanian deadlift (±2SD).

The moving knee sagittal plane ROM was plotted in Figure 3.30, also showing a decreasing trend over recovery. While the moving leg knee is supposed to be kept straight, this metric is an important factor exercise performance compared to recovery. While both legs demonstrate decreased ROM over recovery, the moving leg knee demonstrated a higher ROM when standing on the affected leg versus the unaffected leg. This indicates the unaffected leg was more flexed when moving compared to the unaffected leg. If related to joint ROM recovery, the affected leg is expected to have more flexion, therefore this trend may be an indicator of increased focus or concentration on the affected leg when standing singled legged.

One of the main cues for the RDL is to keep the standing leg straight. Excessive bending or movement in the standing leg is associated with poor strength and/or control. Mean knee ROM and RMS angular velocity for the standing leg are shown in Figure 3.31 and Figure 3.32. Both the standing leg knee ROM and RMS angular velocity increase slightly from day 3 to 6 and then stay consistent. Knee ROM on the affected leg was slightly larger than knee ROM on the unaffected leg, which could be due to increased fatigue or adding weight to the exercise. On day 15 the knee ROM decreases on both the left and right limbs, a good indication of recovery.

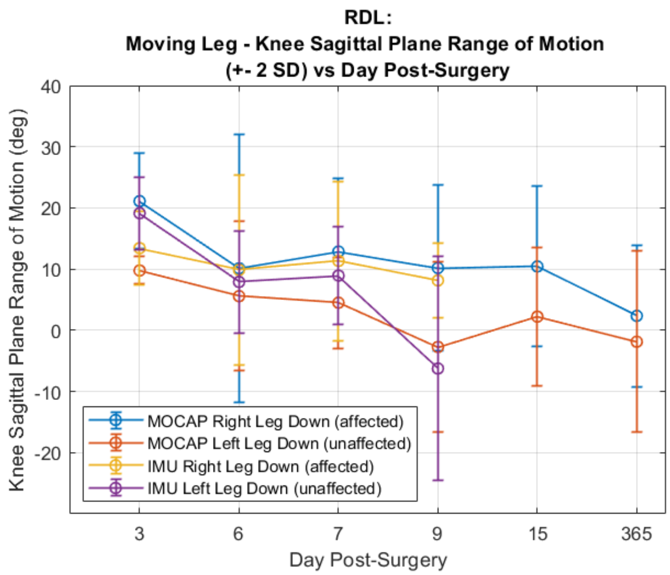

Figure 3.30: Mean knee sagittal plane range of motion for the moving leg during single leg RDL ($\pm$2SD).

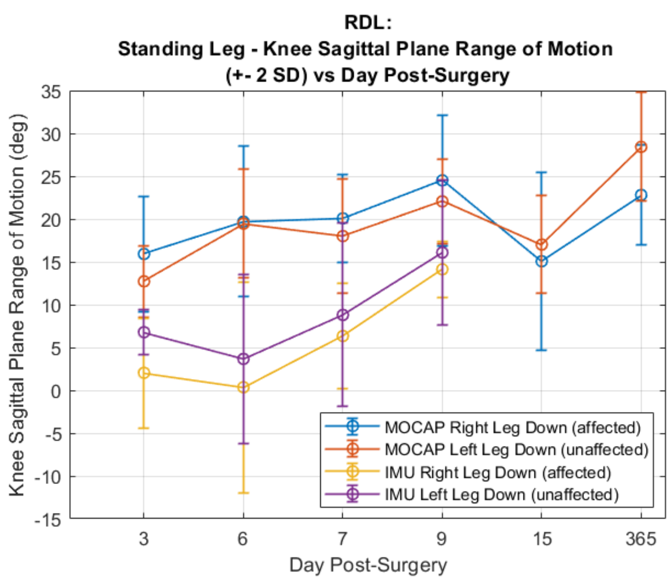

Figure 3.31: Mean knee sagittal plane range of motion in the standing leg during single leg RDL ($\pm$2SD).

RMS knee angular velocity was similar for the right and left across all days. The increased angular velocity across rehabilitation could show recovery or practice, as both limbs showed similar increases as recovery progressed. It may be more likely that angular velocity shows recovery because there was a increase one year post-surgery as well, when only one set of the exercise was performed with no practice sets.

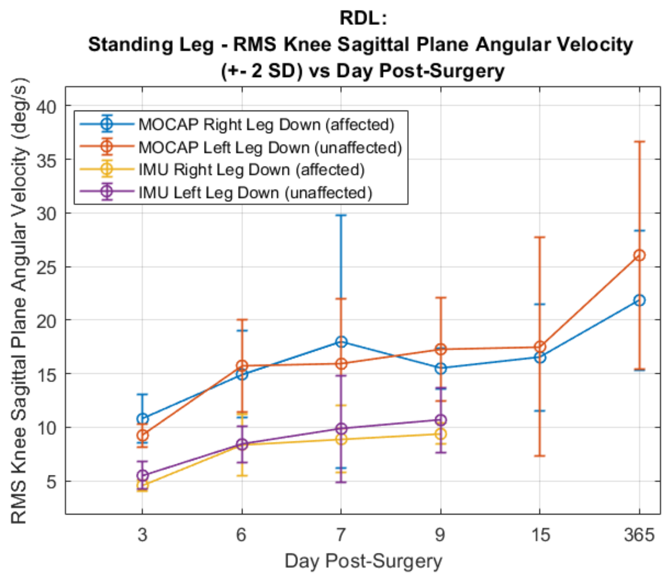

Figure 3.32: Mean RMS angular velocity of the standing leg knee during single leg RDL (±2SD).

The standing hip sagittal plane ROM (Figure 3.33) increases over recovery and is slightly larger on the unaffected side compared to the affected. This ROM is derived from the angular deviation made by the torso moving in relation to the limb standing on the ground. A higher ROM indicates that the patient went further into torso flexion. On day 3 the ROM of the standing hip was 73.0° on the affected limb, which did not reach the desired 90 ° flexion. On day 6 and beyond, the subject reaches a minimum of 94.2° on each limb and the difference between the affected and unaffected limbs decreased to 1.35° by day 9.

Figure 3.34 plots standing leg hip transverse range of motion, where a positive value indicates internal rotation and negative values indicate external rotation. Rotation of the standing leg shows the torso movement about the fixed standing leg. A requirement for successful performance of the RDL is keeping the hips level with each other and parallel to the ground. External opening of the moving hip causes internal rotation of the standing leg, whereas keeping the moving hip closed would cause neutral or external rotation in the standing hip. Hip rotation on the standing leg decreases in both the right leg day and the left leg down over recovery. When the unaffected leg is down, standing leg transverse motion decreases over recovery, potentially indicating improvement through practice. The affected leg also decreases over recovery, although does not decrease at the same rate. This may indicate that there is a continued deficit when the affected leg is down at the end of recovery. Repetition time and time ratio of the time down to the time up were also extracted. Repetition time plots are in Appendix C.

3.7.2 Single Leg RDL Discussion

Statistical significance tests for the RDL recovery metrics are presented in Table 3.11. Significant change was seen in the moving hip ROM on the affected limb between day 7 and 15 post-surgery. These findings support hip ROM as a potential recovery metric for this exercise. The moving limb knee ROM showed significant differences between the affected and unaffected legs on day 7 and 15 post-surgery, indicating a difference between limbs throughout recovery. While no significant change over recovery in the affected limb was observed, a significant increase in knee sagittal plane ROM was found between day 15 and 365. This result may be attributable to variability in exercise performance, and may be difficult to compare to one year post-surgery. Standing knee sagittal plane ROM showed no significant changes over recovery or between limbs, although the change from day 9 to day 15 may indicate significant clinical recovery as a change of 10 ° in the stationary knee (supposed to be straight) is relatively large. 10° is also the largest change between any of the recovery days.

Mean knee RMS angular velocity showed no significant changes between days or limbs despite the largest magnitude increase from day 3 to 6 post-surgery. More information is needed to determine if the trend in knee RMS angular velocity provides any indication of recovery. Mean ROM for the standing hip in the sagittal plane showed only a significant increase from day 3 post-surgery to 15 post surgery on the affected limb. Along with the significant increase in the moving hip sagittal plane ROM, this finding indicates increased recovery of strength and control during this movement (i.e., being able to go deeper into the movement) over recovery.

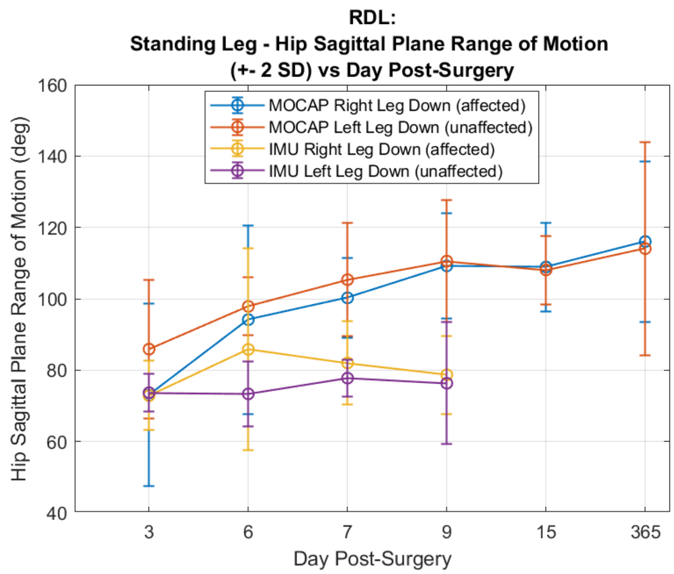

Figure 3.33: Mean sagittal plane hip range of motion for the standing leg during single leg RDL (±2SD).

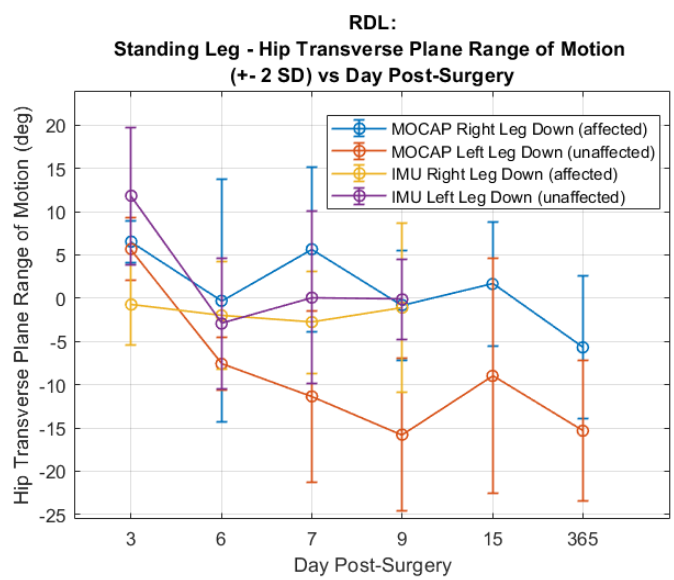

Figure 3.34: Mean transverse plane hip range of motion for the standing leg during single leg RDL (±2SD).

Table 3.11: P-Values for Unpaired T-tests for Single Leg RDLs, for the Affected Leg Between Recovery Days and Between Affected and Unaffected Legs

	Affected vs Unaffected Leg		Affected (Right) Leg Down	
	Day 3	Day 15	Day 3 vs Day 15	Day 15 vs Day 365
		Moving Leg		
ROM	0.264	0.845	0.022	0.311
Abd/Add	0.018	0.009	0.116	0.019
Int/Ext Rotation	0.004	0.037	0.035	0.309
Ankle ROM	0.003	<0.001	<0.001	0.121
Knee ROM	0.004	0.023	0.347	0.034
Knee RMS Angular Velocity	0.008	0.069	0.650	0.379
		Stationary Leg		
ROM	0.199	0.769	0.017	0.262
Abd/Add	0.003	0.018	0.634	0.006
Int/Ext Rotation	<0.001	0.002	0.044	<0.001
Ankle ROM	0.006	0.295	0.049	0.126
Knee ROM	0.216	0.433	0.103	0.004
Knee RMS Angular Velocity	0.241	0.570	0.329	<0.001

3.8 Discussion

Contributions in Chapter 3 include comparison of existing recovery metrics to therapeutic decisions for a patient recovery, presentation and validation of exploratory recovery metrics, and discussion of results clinical significance. Six metrics were presented for supine single leg heel slide. While knee ROM showed recovery over time, range was not fully recovered at day 6 when the exercise was removed from the protocol. Repetition time, knee angular velocity, acceleration, and extension-flexion time ratio were explored as potential metrics. RMS angular velocity, angular acceleration, and repetition time showed significant differences between affected and unaffected limbs that persisted throughout recovery, indicating their importance in the recovery process. Extension to flexion time ratio attempted to quantify patterns seen in joint trajectory data for the knee joint. Significant difference in time ratio was seen between affected and unaffected limbs, however not in the affected limb over recovery. This may indicate no recovery over time or that the metric is not useful in quantifying recovery.

Fifteen metrics were examined for the leg raise. Knee ROM and extension angle are the primary metrics used in clinic through visual observation. Surprisingly, no significant changes in mean values were detected between limbs or over recovery. Hip ROM metrics was extracted for exercise performance purposes, however significant differences were observed between limbs that may have recovery implications. RMS angular velocity, acceleration, and jerk were assessed as a method of monitoring movement in the knee. As a measure of smoothness in the joint, RMS jerk was significantly different only between the affected and unaffected on day 6, and between day 6 and one year post-surgery. While using these exploratory metrics as assessment of the movement is not yet confirmed, they may indicate that the affected leg performs better than the unaffected leg in this exercise. Repetition time and extension to flexion time ratio showed similar results to the heel slide exercise and may be useful in monitoring recovery.

Joint ROM during walking and step length and width metrics were used to assess walking. It is important to note that walking was recovered quickly after surgery, with crutches not used after day 2. Changes in walking metrics were small during recovery, especially joint ROM. Changes in step time, length and width, and asymmetry indices were small. Step length may be the best indicator of recovery as the step length on the affected leg was smaller than the unaffected limb only on day 2, after which it was larger than step length on the unaffected limb. Step length and width asymmetry indices decrease over time as well, possibly good indicators of recovery (e.g., less limping).

Joint ROM, angular velocity, and temporal metrics were assessed for the goblet squat exercise. Hip, knee, and ankle ROM increased over recovery in both limbs, while the affected limb ROM was slightly larger than the unaffected limb on all days. Hip and knee ROM at the end of recovery was significantly smaller than one year post-surgery. Having a healthy baseline for ROM metrics may show limits in recovery that are not otherwise apparent. RMS angular velocity and repetition time showed improvement over recovery, while time ratio stayed consistent across all days of recovery. RDL metrics show recovery over time of depth in the movement and ROM. Metrics for the moving leg, while more important in terms of exercise performance, show trends over the collection period that could be linked to recovery.

This research is limited by the use of one case study patient. Collecting data on a larger subject pool would provide more evidence for validating both current clinical metrics and exploratory metrics, particularly because of inter-subject variability in recovery and baseline measurements. While one case study cannot provide definitive evidence that exploratory metrics should be used when monitoring recovery the goal is to show the potential for these metrics to aid in therapeutic decision making. The case study patient also progressed much more quickly than the general protocol timeline for this procedure. A longer recovery period would generate more data points to validate metrics. Although t-tests were used as a measure of significance, results of the t-test can only provide possible indication because of limited data points both in repetitions and subjects. More repetitions/trials and subjects are necessary to determine true significance because of sample size and to satisfy the condition of independent measures. T-tests on the affected limb over multiple days were technically repeated measures, however the number of repetitions varied throughout recovery limiting applicability of a paired t-test. Walking is particularly prone to intra- and inter- subject variability, and the analysis conducted in the presented case can only provide indications of recovery and remote monitoring feasibility due to limited repetitions (and no intra-subject data). Furthermore, space for walking and fatigue limited walking periods on early days. Fortunately, aid-free walking was recovered quickly and progressed early. A better baseline of the subjects walking characteristics would provide more evidence of changes observed over recovery. The case study rehab progressed more quickly than general timelines prescribed for this surgery and may have implications for comparing this work to the general population. There may be additional limitations in comparing this work to the general population because the case study subject was an athlete with the goal to return to sport.

This work would benefit from collecting more data from patients having undergone a similar procedure or completing similar rehabilitation exercises. With more subjects, data driven methods would be used to generate further rehabilitation metrics that can track and provide insight on recovery of pain, swelling, range of motion, strength, stability, and power. Future work might also include collection of electromyography (EMG) sensor data in a similar verification study to measure muscle activation. EMG generally requires collection of the maximum voluntary contraction (MVC) to normalize the data that could be collected each day in a research setting [78]. Several metrics aim to provide links between kinematic data and strength and power qualities of movement. EMG data would provide further validation that these metrics may be associated with recovery of strength.

Chapter 4

Evaluating IMU-based Monitoring of Recovery

4.1 Introduction

In this chapter, IMU-based measurement error is examined by comparing to reference motion capture over the recovery period. The extended Kalman filter (EKF) has been shown to work well for three dimensional pose estimation from wearable IMUs in an unconstrained space [7], [55]. The case study uses this algorithm to generate IMU-based recovery metrics from joint kinematic data. In this section, IMU metrics are compared to the motion capture equivalent by examining the error and comparing to recovery effect sizes. Effect size is the magnitude of change seen over recovery in the affected limb or the effect between the surgical limb and the healthy limb. Effect size can give an indication of how much change can be expected and whether IMU-based measurement, given a known error, would be able to accurately monitor the change remotely.

Implementation of the the EKF requires setting filter parameters to accurately reconstruct the motion [79]. The process and measurement updates in the EKF each have an associated noise, and changing or tuning the measurement and process noise covariance parameters affects the EKF response [80]. Changing the process noise, which is associated with inaccuracies in the process model, will change how the filter trusts the model prediction. Changing the measurement noise covariance determines how much the filter trusts the measurement. If measurement noise is higher, the filter responds to the measurements more slowly or trusts the measurement less, and vice versa [80].

Different techniques have been used for tuning the noise parameters for the EKF filter for different purposes, to replace the often used trial and error method [81], [82], [79], [80]. Tuning of the EKF noise covariance matrices can be done offline with the use system identification [80]. Maximum likelihood estimates of the state and measurement noise covariance matrices have been used to fine tune EKF algorithms [79]. In a pose estimation setting, the process noise covariance matrix was determined based on the gyroscope output, and the measurement noise covariance matrix was determined based on both the accelerometer and gyroscope outputs [81].

The EKF used for this study was previously validated on healthy subjects and process and measurement noise parameters were determined to generate good performance across a large subject pool [7]. This case study expands on the use of the filter by using it in a rehabilitation setting and attempting to extract recovery metrics and assessing the utility of this algorithm in a remote setting.

4.2 Methods

All IMU metrics were presented in plots in Chapter 3 with the equivalent motion capture ground truth metrics. Plots showed the progression over time with both sensor-based measures and ground truth Vicon-based measures. The average magnitude of error between the sensor-based and motion capture-based recovery metrics were reported for each exercise. The inter-limb and affected limb recovery effect sizes (based on Vicon data) were also reported and compared to the average sensor error. By comparing the effect size to the error indicates whether the metric values from IMU reconstructions can remotely assess patients recovery. The minimum, maximum, and mean values of effect size between the affected and unaffected limb were reported. As well as the effect size of the affected limb between the start of recovery and one year post-surgery and between the start of recovery and the end of the recovery phase, when the exercise was stopped.

The EKF noise parameters were tuned by exercise to optimize the EKF output by minimizing the metric error. First, the EKF was tuned for the heel slide exercise. The same tuning parameters were used on the leg raise exercise to measure the change in metric performance. Noise coefficients were then separately optimized for the leg raise to assess the effects of tuning by exercise.

4.3 Technical Validation: Sensor-Based Metric Error Relative to Motion Capture

4.3.1 Supine Single Leg Heel Slide

This section summarizes the error between the sensor-based metrics, extracted from IMU data, and the motion capture-based metrics. In the plots for each of the metrics above, the yellow and purple lines show the data for the sensor-based metrics for the left (unaffected) and the right (affected) legs, respectively. Motion capture is considered the ground truth or reference values while the IMU metrics are experimental. The IMU to motion capture error is a critical factor of the IMU system and the rehabilitation metrics being used as a remote monitoring tool. The EKF sensor fusion algorithm has been validated against motion capture [7], where data was collected on healthy adults. This case study includes a variety of different exercises collected on one patient during their recovery to test the algorithm in an environment similar to completing exercises at home and the effectiveness for monitoring the recovery for one patient case. Instead of comparing cumulative joint angle trajectory errors, the errors are reported for each metric to encompass the whole process of reconstructing joint kinematics and extracting recovery metrics.

Mean values for the magnitude of error between the two modalities are presented in Table 4.1, with the final column listing average of the absolute error for each metric. Knee range of motion has an average absolute error of 8.15°, while knee extension has an average error of 6.62°. IMU knee ROM and knee extension angle are consistently smaller than the motion capture equivalent. However, knee ROM displayed similar errors on each day and for both legs. In contrast, the relationship between ground truth and sensor-based measures changed day to day for knee extension angle, making it more difficult to track progression remotely (Figure 3.4). This error was larger compared to the 5° average error in visual estimating joint angles in person, however when visual observation is not available, knee sagittal plane ROM recovery may be tracked using the IMUs. Further tuning of the algorithm may also improve the metric error.

Mean RMS angular velocity was $3.76°/s$ and the sensor-based metric means were within 2 standard deviations of the actual measurement on each day. Low magnitude of error is to be expected as the angular velocity from the gyroscope sensor in the IMU is directly used in the EKF algorithm. Angular acceleration error was on average $55.4°/s^2$. RMS angular acceleration had larger error relative to ground truth compared to angular velocity; however, the trend over recovery was consistent. Repetition time is larger or smaller than depending on the day with an absolute mean error of 0.121 seconds. Extension to flexion time ratio has an absolute error of 0.163.

Table 4.1: Magnitude of Error Between the Sensor-Based Metrics and Motion Capture-Based Metrics for Supine Heel Slide

	Day 2		Day 3		Day 6		Average
	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	
ROM(°)	-9.47	-7.41	-8.95	-9.08	-8.13	-5.86	8.15
Extension(°)	-3.32	-10.1	-8.91	-5.51	-5.45	-6.45	6.62
RMS Angular Velocity($^{\circ}/s$)	-3.27	-3.96	-3.38	-3.60	-3.30	-5.04	3.76
RMS Angular Acceleration($^{\circ}/s^2$)	-36.8	-70.0	-38.2	-31.3	-50.8	-105	55.4
Repetition Time(s)	-0.510	-0.033	-0.038	-0.074	-0.070	0.003	0.121
Extension/Flexion Time Ratio	-0.043	-0.094	0.181	-0.141	-0.095	-0.426	0.163

Table 4.2 contains the inter-limb and affected limb effect size over recovery. The inter-limb effect sizes are listed in the first three columns of Table 4.2. The minimum and maximum difference between affected and unaffected legs are in the first and second columns and the mean difference across all days is listed in the third column. Effect size in the affected limb alone between the first day of recovery and one year post-surgery is listed in column 4 and effect size between day one and the end of recovery phase is listed in column 5.

Average knee range of motion error (8.15°) was less than the effect sizes on the affected limb at end of phase (32.4°) and one year post-op (36.7°). Considering the error is greater than the smallest inter-limb effect size of 4.60°, the algorithm may not be able to compare between limbs at end stages of recovery when the ROM difference between limbs decreases. Visual estimation generates an error of $\approx 5^{\circ}$, making it more accurate compared to the untuned algorithm estimates in this case study. The error in values of maximum knee extension angle between IMU and ground truth was greater than the effect size in knee extension angle over recovery and between limbs. The IMU to motion capture error for RMS angular velocity and RMS angular acceleration were lower than all effect sizes over recovery. As previously mentioned, the sensor-based metrics also have similar errors on each day and track the recovery trends well.

Both the time metrics, repetition and time ratio, are reliant on identification of key repetition events. Small errors between in time-related metrics indicated that it was acceptable to use patterns in the joint angle trajectories to separate repetitions. Average repetition time error was $0.170s$ smaller than the minimum inter-limb effect size of $0.291s$, which was also the smallest effect size measured throughout recovery. This further supports sensors metrics would be able to measure recovery in repetition time remotely. Changes in

Table 4.2: Heel Slide Inter-Limb and Affected Limb Effect Size Over Recovery Compared to Mean Metric Error

	Inter-Limb Effect Size			Affected Limb Effect Size		
	Min	Max	Mean	1-Year Post	End of Phase	Mean Error
ROM(°)	4.60	39.7	17.2	36.7	32.4	8.15
Extension(°)	0.034	3.03	1.23	1.62	2.24	6.62
RMS Angular Velocity($^{\circ}/s$)	20.9	55.6	42.8	82.4	42.1	3.76
RMS Angular Acceleration($^{\circ}/s^2$)	117	254	176	239	124	55.4
Repetition Time(s)	0.291	3.95	2.15	4.14	2.70	0.121
Extension/Flexion Time Ratio	0.113	0.570	0.390	0.201	0.116	0.163

extension-flexion time ratio between the start of recovery and the end of phase, and differences between legs, were smaller than the mean error measured. Although both the IMU and motion capture showed similar recovery trends and relationship between right and left legs (Figure 3.8), the error exceeds the effect size and may not accurately demonstrate recovery.

4.3.2 Supine Straight Leg Raise

Table 4.3 lists the magnitude error between sensor-based and motion capture-based measures for the leg raise exercise. Magnitude error indicates of how far off the IMU reconstructions are from the ground truth, and percent error shows the error as a proportion of the trusted value. This offers insight on how the sensors will perform in a remote setting when they are the only source of data. The major difference in this exercise compared to the heel slide is minimal movement in the knee joint. As the IMU is comprised of rate sensors, when there is little to no movement in a joint, the reconstruction can succumb to drift and other noise artifacts will be more prevalent compared to the motion.

Error for the knee ROM metric was on average 1.51°. It was smaller on the IMU reconstruction than the ground truth on all days except the right leg raise on day 3. The magnitude error was on average 6.64° less for the leg raise compared to the heel slide. The IMU data in Figure 3.10 showed similar trends compared to the motion capture data. Knee range of motion was greater on the unaffected leg on day 2 and 3, after which the knee ROM was greater on the right leg compared to the left leg. The magnitude errors for the actual values of max extension and flexion for leg raise were 3.30° and 2.31°. By comparison, the heel slide had a greater average magnitude error for the actual knee extension angle of 6.62°. Trends in the actual values of max knee extension and flexion angles were also

Table 4.3: Magnitude of Error Between the Sensor-Based Metrics and Motion Capture-Based Metrics for Supine Single Straight Leg Raise

	Day 2		Day 3		Day 6		Average
	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	
ROM (°)	-3.65	-2.37	0.345	-2.30	-0.11	-0.30	1.51
Extension (°)	-4.46	-5.23	-3.64	-0.983	-1.25	-4.25	3.30
Flexion (°)	0.611	2.86	3.98	-1.32	1.14	3.95	2.31
Hip ROM (°)	-13.8	11.2	-10.1	30.4	-6.06	-3.55	12.5
Hip Abd/Add (°)	-14.4	19.7	-11.5	29.1	-8.78	-1.79	14.2
Hip Rotation (°)	-4.10	67.8	-3.93	94.6	6.22	24.7	33.5
RMS Angular Velocity ($°/s$)	-2.47	-2.56	-0.144	-0.815	0.820	-2.32	1.52
RMS Angular Acceleration ($°/s^2$)	-48.4	-44.1	-17.4	-40.8	-35.8	-86.5	45.5
RMS Jerk ($°/s^3$)	-1.20e+03	-1.01e+03	-451	-1.05e+03	-986	-1.73e+03	1.07e+03
Repetition Time (s)	-0.495	0.068	-0.224	-0.341	-0.147	-0.094	0.228
Extension/Flexion Time Ratio	0.247	0.034	-0.012	-0.049	0.095	-0.008	0.074
Time Offset (s)	-1.65	-0.183	0.643	-0.083	-0.773	-1.40	0.789

similar in that the unaffected leg had both higher flexion and lower extension angles than the affected leg (Figure 3.12 and Figure 3.11).

Hip sagittal plane ROM had larger error (12.5°), compared to the knee joint ROM (1.51°). Trends in the hip ROM for the motion capture and IMU show that the right hip range of motion was smaller the the left hip, although the right leg was generally underestimated compared to motion capture and the left leg was generally overestimated compared to motion capture (Figure 3.13). The large error on day 3 may be explained by movement speed. As acceleration was modelled as a constant, large changes in acceleration result in errors between the expected and estimated measurements. The algorithm attempts to minimize this error in the next time step, which results in overestimating the joint angle reconstruction if acceleration is not maintained. The hip frontal plane ROM had a similar average magnitude error of 14.2°. When laying down, the hip abduction-adduction joint is about the vertical axis, making the measurement more susceptible to noise without causing errors in the EKF output. Additionally there was little movement in the abduction-adduction direction making the estimation susceptible to drift.

A potential source of large errors on day 2 and 3 for the left leg, was a change in calibration motion on day 6. The calibration motion moved the leg out of frontal plane which helped minimize the drift initially. Similar issues occurred with the hip external-internal rotation axis, where the magnitude error was on average 33.5°. These large errors indicate hip abduction-adduction and internal-external rotation measures are less reliable to inform decision making remotely. Hip sagittal plane ROM provides better estimates compared to motion capture and trends in the IMU data correspond to trends in the motion capture data.

Error in average knee joint RMS angular velocity was $1.52°/s$ and RMS angular acceleration error was $45.5°/s^2$. This was $2.24°/s$ and $9.9°/s^2$ less than the respective errors for heel slide. Average angular jerk had a magnitude error between IMU and motion capture of $1.07e{+}03$. Another issue besides the error between the two modalities was consistency of the error. The three rate metrics do not show the same trends throughout recovery. While the left leg ground truth angular velocity was always greater than the right leg, the IMU shows the right leg having larger angular velocity on day 6 (Figure A.3). Because there is limited movement in the knee joint leading to larger mean errors, the use of these metrics remotely may be limited for this exercise.

Time offset between time of maximum hip flexion and maximum knee flexion during each repetition was the final exploratory metric. The same method was used for both the motion capture metrics and sensors-based metrics with an error between the two of $0.789s$. The disparity in this metric was most likely because of the noise in the knee joint angle trajectory for the IMU reconstructions. Clear sinusoidal patterns that align with repetition start and end points were seen in knee joint angle for the motion capture, whereas this pattern was noisier in the IMU knee joint angle trajectories.

Table 4.4 compares the average metric error (last column) to the inter-limb and affected limb effect size over recovery. Mean error for knee range of motion was similar to mean inter-limb effect sizes and effect size in the surgical leg. While maximum values for effect size between legs were greater than the average error, measuring improvement in the affected limb may not be possible remotely. Mean error for knee flexion and knee extension angles were generally larger than the effect sizes during rehab. Unless there were larger effect sizes in the patient, IMU-based measurement of these metrics might not accurately indicate recovery.

In this case study, the sensor data does show similar relationship between legs which could be used as a comparison. Hip range of motion was more of an exercise performance and exploratory recovery metric. The sagittal plane ROM error was smaller than the effect size between the start of recovery and one year post-surgery, but a similar magnitude to the effect size during the recovery phase (when leg raise was performed). Mean error was similar to the mean inter-limb effect size, as well. Hip abduction-adduction error was in the same range as effect size, and internal-external range of motion error was much larger than effect size. This metrics may be used to assess generally whether the exercise was being performed correctly, however, potential changes due to recovery could not be measured accurately.

RMS angular velocity error was larger or in the same range as the effect seen during

Table 4.4: Leg Raise Inter-Limb and Affected Limb Effect Size Over Recovery Compared to Mean Metric Error

	Between Limb Effect Size			Affected Limb Effect Size		
	Min	Max	Mean	1-Year Post	End of Phase	Mean Error
ROM	0.164	3.75	1.34	1.36	1.50	1.51
Extension	2.27	3.14	2.77	1.35	0.19	3.30
Flexion	1.50	6.89	3.46	0.020	1.69	2.31
Hip ROM	6.98	17.6	11.4	24.6	7.48	12.5
Hip Abd/Add	14.4	32.1	24.9	12.7	1.62	14.2
Hip Rotation	0.079	5.09	3.34	6.06	6.87	33.5
RMS Angular Velocity	0.057	4.35	1.87	0.893	0.128	1.52
RMS Angular Acceleration	2.18	47.3	24.7	27.3	3.05	45.5
RMS Jerk	82.3	775	452	1.00E+03	78.1	1.07E+03
Repetition Time	0.122	1.21	0.633	1.93	1.22	0.228
Extension/Flexion Time Ratio	0.032	0.154	0.112	0.096	0.116	0.074
Time Offset	0.073	0.584	0.314	0.188	0.477	0.789

recovery. Changes over recovery are small and may be undetectable using sensor based metrics. The relationship between left and right leg angular velocity and the significance of the difference between them is questionable. Sensor data shows a similar relationship between left and right legs on all days except day 6, which would be accounted for based on the error compared to effect size. RMS angular acceleration and RMS angular jerk similarly had higher errors than most effect sizes in Table 4.4. Repetition time error was smaller than the effect size in the affected limb over recovery and from day 1 of recovery to 1 year post-surgery. This metric could be used remotely with current average error to assess recovery of repetition time. In cases where the difference between limbs is smaller this metric may not perform well, however small differences in repetition time would not provide clinically significant recovery results. Time ratio is smaller than most effect sizes over recovery, while time offset error is larger than any effect size seen over recovery.

4.3.3 Straight Line Over-Ground Walking

Average joint angle error in the hip joints and ankle sagittal plane joint were 6.46°, and 7.12°. Sagittal plane hip motion is underestimated by the sensor-based metrics for both the affected and unaffected legs. The average error is 6.04° lower than the average error in hip sagittal plane joint angle error in the leg raise exercise. IMU data shows the affected leg has a smaller range of motion only on day 2. The motion capture data in comparison shows the affected leg having a smaller range of motion on all days of recovery. In the frontal plane, joint angle estimation error is 8.71° lower during walking compared to the leg raise. The EKF estimation may be better when the body is in upright orientation of walking. During walking, both joints experience more motion as well, which may help minimize drift in these axes. The case study patient does not suffer from spastic gait where sudden changes in segment speed might affect the EKF output. Hip frontal plane joint angle was underestimated in both limbs on all days of recovery (Figure 3.25).

Table 4.5: Magnitude of Error Between the Sensor-Based Metrics and Motion Capture-Based Metrics for Straight Line Overground Walking

	Day 2		Day 3		Day 6		Average
	Right Leg	Left Leg	Right Leg	Left Leg	Right Leg	Left Leg	
Hip ROM	-3.62	-2.73	-8.01	-7.22	-6.32	-10.9	6.46
Hip Abd/Add	-2.97	-10.30	-4.45	-7.67	-6.98	0.581	5.49
Ankle ROM	-5.45	-8.43	-5.13	-6.18	-9.53	-7.99	7.12
Knee ROM	-12.0	-16.6	-24.3	-12.4	-23.8	-20.3	18.2
Step Time	0.022	-0.042	-0.002	-0.008	0.041	-0.057	0.029
Step Length	0.110	0.005	0.066	-0.029	-0.034	-0.003	0.041

Both hip joints showed similar trends in the motion capture and IMU metrics on day 2 and 3, between the affected and unaffected leg. On day 6, the IMU shows the opposite leg has greater frontal plane ROM on average compared to motion capture. Knee ROM error is on average 18.2° compared to heel slide error of 8.15° and leg raise knee range of motion error of 1.51°. Average step time error was $0.029s$ and average step length error was $0.041m$.

Table 4.6 lists the effect size between limbs and the effect size over recovery. Although step length error was low, the maximum difference between the left and right step lengths was $0.039m$. The error was approximately the same magnitude as the difference detected between the affected and unaffected limbs and improvement over time. The improvement in step length over the recovery phase was $0.083m$, approximately double the average error. Clinicians may not be able to use this metric remotely to detect small differences in step length between limbs, but might be able to track recovery over time. Average step time error was $0.029s$, approximately equal to the mean inter-limb effect size and smaller than the improvement over recovery and the change from the start of recovery and one year post-surgery. Hip range of motion error in the sagittal and frontal planes was larger than than any effect size seen in recovery for this subject.

Table 4.6: Overground Walking Inter-Limb and Affected Limb Effect Size Over Recovery Compared to Mean Metric Error

	Between Limb Effect Size			Affected Limb Effect Size		
	Min	Max	Mean	1-Year Post	End of Phase	Mean Error
Hip ROM	0.598	4.58	2.39	6.35	4.71	6.46
Hip Abd/Add	0.410	2.79	1.67	3.08	4.30	5.49
Ankle ROM	0.141	2.64	1.47	9.30	0.366	7.12
Knee ROM	1.78	3.77	2.62	6.77	8.66	18.2
Step Time	0.012	0.048	0.025	0.056	0.098	0.029
Step Length	0.005	0.039	0.016	0.083	0.069	0.041

Average ankle error was smaller than the effect size seen in the affected limb over the recovery phase. Knee range of motion error was larger than any effect size during this case study for walking. In general, effect sizes were smaller than the average error. In cases with larger effect sizes, this algorithm may be more useful for remote monitoring. The limited sample size for walking likely also factors in to the large error and different trends in data between modalities.

4.3.4 Double Leg Goblet Squat

Overall, sensor-based metrics showed similar trends as motion capture-based metrics, however magnitude error was larger for most metrics compared to other exercises. The trends across the recovery period followed more closely to motion capture-based trends compared to leg raise and walking. Although not ideal, sensors could still be used remotely to track progress if the recovery trend is similar. Table 4.7 shows the magnitude error between motion capture and IMU recovery metrics.

Hip flexion-extension had on average 48.4° of error over day 7 and 9 and between both legs. Average hip abduction/adduction error was 38.2° and average hip transverse plane error was 34.8°. Compared to the leg raise, hip ROM error increased by 35.9° in the sagittal plane, 24° in the frontal plane, and error was similar in the transverse plane. There is initial drift before the movement starts in hip internal-external rotation that may be the cause of the increased error in the other two hip joint movements. The hip sagittal plane range did show an increase in range of motion from day 7 to day 9 , which motion capture also showed (Figure 3.24).

Table 4.7: Magnitude of Error Between the Sensor-Based Metrics and Motion Capture-Based Metrics for Double Leg Goblet Squat

	Day 7		Day 9		Average
	Right Leg	Left Leg	Right Leg	Left Leg	
Hip ROM	57.6	45.5	49.8	40.9	48.4
Hip Abd/Add	-57.7	-35.5	-36.6	-23.2	38.2
Hip Rotation	39.4	37.3	40.4	22.3	34.8
Ankle ROM	3.74	2.03	4.91	1.30	2.99
Knee ROM	-19.3	-13.8	-14.6	-6.87	13.6
Knee RMS Angular Velocity	-21.0	-14.1	-19.9	-9.84	16.2
Time Ratio	0.337		0.115		0.113
Repetition Time	-0.007		-0.037		0.011

In the reconstruction, abduction-adduction angle starts normally and as the knees get closer to the chest, they begin to drift inwards in adduction, compared to the motion capture ground truth where the knees remain turned outward in hip abduction. IMU metrics showed an upward trend indicating less adduction on day 9 compared to day 7, which corresponds to a lower knee valgus angle (Figure 3.25). The same trend was present in the motion capture data, although the increase in adduction was 2.49° in the motion capture data and 13.2° in the IMU data.

Ankle and knee ROM measurements had an average error of 2.99° and 13.6°, respectively. Ankle flexion-extension angle error was 3.5° less than the error for walking. Both magnitude error was low, and IMU metrics showed similar trends as the motion capture data in increased ankle ROM between the two days IMU data was collected (Figure 3.26). Ankle sagittal plane ROM error was 3.5° lower for goblet squats than walking. Knee range of motion error on average was 13.6°, 5.45° larger than the mean error for heel slide, 12.1 ° larger than the error for leg raise, and 4.6 ° less than the mean error for walking. The increased error in hip abduction-adduction joint reconstruction may be carried forward and result in a greater knee joint reconstruction error compared to heel slide and leg raise exercises. Knee joint ROM increased over time for both the sensor and motion capture-based metrics (Figure 3.23). Using this tool remotely might show increasing trends but not the true magnitude of knee flexion-extension.

Sagittal plane knee joint RMS angular velocity was on average 16.2°$/s$, and was larger than the error for heel slide and leg raise. Knee angular velocity showed the same increasing trend in both sets of data. The difference between day 7 and 9 for the motion capture was 8.36° and the difference for the IMU metrics between days was 9.52°. Clinicians could potentially use this remotely to track the increasing trend in knee angular velocity during goblet squats. Repetition time, determined using the start and end points of the exercise corresponding to minimum knee joint angle, had low magnitude error. The time ratio is calculated using these points as well as max knee flexion, corresponding to the bottom of the squat. Time ratio metric error was 0.113 between ground truth and IMU, and the two data sets did not follow the same trends over recovery (Appendix B).

Table 4.8 presents effect sizes over recovery and mean metric error. The changes in hip sagittal plane ROM over recovery and the difference between legs was smaller than the mean metric error. The effect between the first day squat exercises was performed and one year post-surgery was the closest value to the average error, however was still 14.9° smaller. Hip abduction-adduction ROM error was much larger than any effect size seen in this joint. Given the current configuration, monitoring hip ROM remotely may not be possible beyond reflecting trends in both limbs, and data from more patients would need to be tested to confirm.

Table 4.8: Goblet Squat Inter-Limb and Affected Limb Effect Size Over Recovery Compared to Mean Metric Error

	Between Limb Effect Size			Affected Limb Effect Size		
	Min	Max	Mean	1-Year Post	End of Phase	Mean Error
Hip ROM	0.851	4.79	3.12	33.5	5.63	48.4
Hip Abd/Add	0.096	3.51	1.60	2.92	3.77	38.2
Hip Rotation	3.21	14.23	8.87	33.3	6.49	34.8
Ankle ROM	0.129	4.57	1.81	0.425	5.10	2.99
Knee ROM	1.20	5.70	3.46	32.4	7.95	13.6
Knee RMS Angular Velocity	3.13	9.40	5.98	29.7	41.4	16.2
Time Ratio				0.051	0.062	0.113
Repetition Time				0.147	0.692	0.011

Ankle ROM effect size over recovery was was larger than the average error and the data from this joint showed an increasing trend in both the right and left limbs. The error is however larger than the effect sizes between the right and left ankles on the days that IMU data was collected. This metric may be able to assess recovery or improvement over time, but unlikely to measure slight differences between legs. Knee flexion-extension ROM error was larger than the effect sizes. Mean error was lower than the effect size compared to one year post-surgery, however, the error makes tracking during recovery difficult. RMS angular velocity may be trusted remotely to measure increases over recovery as the error is smaller than the effect size on the affected limb, but not to measure differences between legs during the goblet squat. The error for time ratio was larger than both effect sizes, although the motion capture data did not show clear recovery trends. Finally, repetition time error was less than the effect size for goblet squat, further supported by the IMU data corresponding with the decreasing trend of the motion capture data.

4.3.5 Single Leg Romanian Dead Lift

Errors between sensor-based and motion-capture based metrics are listed in Table 4.9, as well as the average error for each metric across all days. The magnitude error was different for the same metrics on the moving versus stationary leg. Moving hip sagittal plane ROM error was 6.32°, while the stationary hip ROM error was 19.5°. Similarly, knee sagittal plane error on the moving leg was 3.89° and the stationary knee sagittal plane error was 11.8°. Sensor-based metrics for the moving hip ROM show a similar decreasing trend over recovery, same relationship between affected and unaffected limb, and demonstrate low error, supporting accurate reconstruction remotely. Stationary leg hip sagittal plane ROM is underestimated by the sensor-based metrics and the trends contradict motion capture-based metrics. Sensor-based metrics for the moving leg knee sagittal plane ROM show the same trends as ground truth, with larger affected leg ROM compared to the unaffected limb. Stationary knee range of motion shows the opposite trend for sensor versus motion capture data. It is important to look at both moving and stationary leg metrics because metrics from the moving limb may be tied to recovery of strength and control on the stationary limb as well as exercise performance.

Table 4.9: Magnitude of Error Between the Sensor-Based Metrics and Motion Capture-Based Metrics for Single Leg RDL

	Day 3		Day 6		Day 7		Day 9		Average
	Right Leg Down	Left Leg Down	Right Leg Down	Left Leg Down	Right Leg Down	Left Leg Down	Right Leg Down	Left Leg Down	
Moving Leg									
ROM	-7.49	-11.3	-6.99	-1.69	-3.17	-8.76	4.43	-6.74	6.32
Abd/Add	-28.1	-28.5	-15.0	4.70	-8.15	9.96	1.29	28.3	15.5
Int/Ext Rotation	6.81	-16.3	14.5	5.83	13.2	12.9	18.5	20.1	13.5
Ankle ROM	-9.50	-6.61	-16.0	-11.3	-9.89	-13.4	-9.97	-7.40	10.5
Knee ROM	-7.67	9.36	-0.259	2.33	-1.53	4.44	-2.04	-3.52	3.89
Knee RMS Angular Velocity	-1.49	2.36	-2.90	-2.14	-2.11	-1.53	-3.43	-2.78	2.34
Stationary Leg									
ROM	-0.115	-12.2	-8.33	-24.5	-18.2	-27.6	-30.5	-34.2	19.5
Abd/Add	-0.762	3.50	-6.93	-16.08	-9.38	-8.75	-12.3	-9.17	8.36
Int/Ext Rotation	-7.28	6.16	-1.69	4.66	-8.42	11.42	-0.291	15.63	6.94
Ankle ROM	11.9	6.26	7.15	6.56	8.87	2.63	3.68	1.83	6.10
Knee ROM	-13.9	-5.94	-19.3	-15.8	-13.7	-9.20	-10.4	-5.97	11.8
Knee RMS Angular Velocity	-6.20	-3.75	-6.56	-7.33	-9.08	-6.06	-6.10	-6.62	6.46
Time Ratio	-0.153	-0.076	0.129	0.076	0.080	-0.148	-0.056	0.043	0.095
Repetition Time	-0.924	-0.570	-0.648	-0.417	-0.839	-0.260	-0.526	-0.297	0.560

Conversely, hip abduction-adduction and internal-external rotation have higher average error in the moving limb compared to the stationary limb. For both legs, there was very little movement in these axes, contributing to larger errors. Moving hip abduction-adduction error was 15.5° versus the error for the stationary hip was 8.36°. Standing hip frontal plane range of motion is a measure of keeping the hips level during the exercise. Both sensor-based and motion capture metrics show a downward trend, where the unaffected leg is further abducted compared to the affected leg. Both the difference between legs (5°) and the affected leg hovered around 0° indicate level hips. Considering change in the affected leg over recovery was 2.87° and average error was 8.36°, sensors may lack sufficient accuracy to measure this change. However, an effect of 2.36° may not be clinically relevant, particularly by visual assessment.

Inter-limb and affected limb effect sizes are listed in Table 4.10. Moving hip ROM error was lower than the change in affected leg recovery and between day 1 and one year post-surgery. Error was also lower than the maximum difference between limbs, but larger than the mean effect size. The disparity between limbs may not be detectable using the sensors, but recovery over time would be captured. Similarly, stationary hip ROM effect size was only larger than the average error when measuring the effect over recovery. Hip frontal plane angle error is smaller than recovery effect size only for the moving limb.

Hip transverse plane ROM would be important to measure in the standing limb to indicate level hips. Noticeable opening of the hips, indicated by internal rotation at the hip joint would indicate performing the exercise incorrectly. The error between sensor and motion capture data was smaller than the effect size in the affected limb and the mean difference between limbs. The change in stationary knee ROM over recovery is an increase of 8.59°, the effect size is smaller than the error. A main cue of the RDL is keeping the stationary leg straight, decreasing the error might be critical to determining changes in this angle over time. If deviations less than 11.8° are considered acceptable, then the IMUs might be able to provide clinical information remotely. The moving limb sagittal plane knee ROM error was lower than the minimum difference between limbs and lower than recovery effect size. Moving leg sagittal plane metrics would be good candidates for remote monitoring of recovery and exercise performance in this case study.

The ankle range of motion is not especially important for the RDL. The ankle angle in the stationary leg would be more important for indication of stability. Stationary ankle joint error was 2.29° less than change detected over recovery and 4.9 ° less than change detected between recovery and one year post-operation. Considering error was larger than the mean difference between limbs, effects larger than 6.10° may be detected potentially indicating ankle instability. Moving knee RMS angular velocity increased by $4.83°/s$ over recovery, larger than the average error for the metric. The stationary knee RMS angular

Table 4.10: Single Leg RDL Inter-Limb and Affected Limb Effect Size Over Recovery Compared to Mean Metric Error

	Between Limb Effect Size			Affected Limb Effect Size		
	Min	Max	Mean	1-Year Post	End of Phase	Mean Error
Moving Leg						
Hip ROM	0.736	8.56	3.53	16.1	12.7	6.3
Hip Abd/Add	0.331	9.08	5.75	18.5	11.3	15.5
Hip Rotation	2.66	8.67	5.77	1.26	2.63	13.5
Ankle ROM	5.06	21.9	15.6	1.83	0.978	10.5
Knee ROM	4.43	12.9	8.46	18.5	10.7	3.9
Knee RMS Angular Velocity	3.32	7.69	5.34	7.03	9.61	2.3
Stationary Leg						
ROM	0.827	12.9	4.34	42.8	35.9	19.5
Abd/Add	0.013	7.99	4.78	0.295	5.17	8.36
Int/Ext Rotation	0.860	17.7	10.1	12.5	4.90	6.94
Ankle ROM	0.623	7.02	4.06	11.0	8.39	6.10
Knee ROM	0.235	5.49	2.57	7.01	0.85	11.8
Knee RMS Angular Velocity	0.801	3.99	1.90	11.3	5.75	6.46
Time Ratio	0.002	0.219	0.105	0.159	0.028	0.095
Repetition Time	0.144	2.44	1.21	5.00	3.11	0.560

velocity also increased by $7.1°/s$ over recovery, also larger than the average error of $6.46°/s$ in this metric. Although clinical significance is yet undetermined, RMS angular velocity in the knee joint may be monitored remotely given changes are generally larger than the average error.

Repetition time effect size over recovery was 2.70 s while the error was only 0.560 s. Time ratio similarly has a smaller error (0.095) compared to effect size (0.1121). Repetition time showed a steady decrease throughout recovery and may be used to judge comfort and ease of motion. Time ratio also had a decreasing trend and the affected leg time ratio remained smaller on all days (Appendix C).

4.4 Tuning of EKF Parameters for Minimizing Recovery Metric Errors

As discussed accuracy of the recovery metric reconstruction using the EKF was varied between exercises, between limbs, and recovery days. For some metrics, the EKF reconstruction provided good results supporting monitoring of recovery, whereas others were more difficult to track. For some exercises, like the single leg raise, the knee joint ROM error was on average 1.51°, but the hip range of motion error was much larger at 12.5°. For the lying heel slide, mean metric error for knee ROM was 8.15°, higher than published values of 6.20° [7].

Recovery metric errors presented in this work so far were all using the same EKF parameters. Error differences between the exercises motivated tuning the filter parameters by exercise to optimize the reconstruction for each recovery exercise. Theoretically, if the exercise was known the tuning parameters could be set for the specific recovery exercise and improve reconstruction performance. As most of the recovery exercises in this case study are prescribed for a multitude of injuries and procedures, the parameters would be applicable for many different rehabilitation protocols. In this section, a EKF tuning method is described to examine the potential for exercise-specific tuning.

Initial selection of EKF noise parameters were set so the motion reconstructions did not diverge. Accelerometer and gyroscope measurement noise parameters were set to 1.00E-00 and 1.00E-02 respectively. First, four noise parameters were selected for the accelerometer (1.00E-02, 1.00E-01, 1.00E01. and 1.00E02) while keeping the gyroscope noise constant. Then, four noise parameters were selected for the gyroscope (1.00E-00, 1.00E-01, 1.00E-03. and 1.00E-04) while keeping the accelerometer noise constant. Recovery metrics were extracted for each of the cases and compared to the original.

The initial search yielded error improvements by increasing gyroscope noise or decreasing accelerometer noise. Changing the gyroscope noise parameter by a factor of 10 decreased error by 2.66° compared to 1.82° when changing the accelerometer by a similar factor. Moving forward, the results from tuning gyroscope noise are reported, due to stronger performance improvements. Table 4.11 lists the error for the recovery metrics using different gyroscope tuning parameters compared to the original in the middle column of 1.00E-02.

Changing gyroscope noise so that the error metrics are better increased drift in the hip abduction/adduction direction on some days, although it did not cause errors in the EKF output. The more gyroscope noise was increased, the larger the drift was in hip abduction-adduction joint. Although there was drift and inaccuracies in hip abduction-adduction

Table 4.11: Average Metric Error for Each Gyroscope Tuning Case for Heel Slide

	1.00E+00	1.00E-01	1.00E-02	1.00E-03	1.00E-04
ROM (°)	4.66	5.49	8.15	9.66	7.92
Extension (°)	3.57	4.89	6.62	13.0	24.3
RMS Angular Velocity ($^\circ/s$)	1.29	2.18	3.76	4.21	3.46
RMS Angular Acceleration ($^\circ/s^2$)	48.1	53.7	55.4	53.1	46.1

ROM compared to motion capture using the original filtering parameters, using 1.00E-01 as the gyroscope noise increased the drift from ≈40° to ≈100° on several days.

Fine tuning of the gyroscope noise was performed by using tuning parameters between the original and 1.00E-01, where hip abduction trajectories were similar to the base tuning parameter. Fine tuning of the gyroscope noise was explored to determine the balance between accuracy and minimizing drift in the frontal plane, as shown in Table 4.12. Knee range of motion error decreased by 2.43° corresponding to 91.4% of the decrease achieved when setting the gyroscope noise to 1.00E-01.

Table 4.12: Average Metric Error for Fine Tuning Gyroscope Measurement Noise Parameters for Heel Slide

	1.00E-01	7.00E-02	1.00E-02
ROM (°)	5.49	5.72	8.15
Extension (°)	4.89	5.06	6.62
RMS Angular Velocity ($^\circ/s$)	2.18	2.34	3.76
RMS Angular Acceleration ($^\circ/s^2$)	53.7	53.8	55.4

The main issue with assessing the effect on frontal plane joint angle trajectories was the variation between each collection when changing gyroscope noise parameters. Comparing 7.00E-02 to 1.00E-0.1, there was less drift in the right leg on day 2 (≈40° compared to ≈60°), however there was more drift in the right leg on day 3 (≈40° compared to ≈0°). Additionally, on day 6 the drift in the left leg was larger initially, however the reconstruction of the joint trajectory during the motion was more accurate to the motion capture.

To compare the same tuning parameters on a different exercise, the leg raise trials were processed using the same set of four different gyroscope tuning parameters that were initially used for the heel slide. Table 4.13 lists the recovery metric errors for the different cases of gyroscope tuning parameters. Where the heel slide metrics improved with

Table 4.13: Average Metric Error for Each Gyroscope Measurement Noise Parameter Case for Leg Raise

	1.00E+00	1.00E-01	1.00E-02	1.00E-03	1.00E-04
ROM (°)	2.95	1.83	1.51	1.38	1.54
Extension (°)	3.64	3.32	3.30	5.51	7.65
Flexion (°)	1.25	1.61	2.34	4.45	7.27
Hip ROM (°)	28.5	10.5	12.5	27.5	20.9
Hip Abd/Add (°)	15.9	14.6	14.2	16.1	13.0
Hip Rotation (°)	7.72	29.6	33.5	25.2	15.3
RMS Angular Velocity ($°/s$)	1.59	1.55	1.52	1.00	1.22
RMS Angular Acceleration ($°/s^2$)	30.8	44.7	45.5	37.7	30.8
RMS Jerk ($°/s^3$)	933	1.07E+03	1.07E+03	998	934

increasing gyroscope noise, the majority of error metrics were the lowest when keeping the gyroscope tuning at 1.00E-02 or decreasing the gyroscope noise to 1.00E-03. Knee range of motion and RMS angular velocity, acceleration, and jerk error were improved by decreasing gyroscope noise. Actual values of knee flexion and extension were the best at 1.00E-02 or only slightly increased by increasing the gyroscope noise. Hip abduction-adduction increased error by either increasing or decreasing gyroscope noise. Hip sagittal plane range of motion error increased when decreasing gyroscope noise, however hip internal-external range of motion error decreased by 8.3°. Although hip sagittal plane ROM error decreased when increasing gyroscope noise, the decrease in knee sagittal plane ROM, RMS angular velocity, and hip internal/external rotation suggested that using a lower value for gyroscope noise may improve the error metrics. The same exercises were processed using 5.00E-0.5 and average errors are reported for this case in the middle column of Table 4.14.

Knee ROM error decreased from the original tuning parameter, although an improvement of 0.13° is small and not clinically relevant. Knee extension and flexion angle error increased by 0.32° and 0.28° respectively; these changes are also not physically relevant, however the error was already low. Hip sagittal plane ROM error decreased by 3.25°, compared to a 2.00° decrease when the gyroscope noise tuning parameter was set at 1.00E-01. Hip abduction-adduction ROM error decreased to 12.5° from 14.2° and hip rotation ROM decreased form 33.5° to 27.6°. All rate metric errors also decreased when using 5.00E-03 as the gyroscope measurement noise parameter. The majority of metric errors improved when decreasing the noise gyroscope noise.

Table 4.14: Average Metric Error for Fine Tuning Gyroscope Measurement Noise Parameters for Leg Raise

	1.00E-02	5.00E-03	1.00E-03
ROM (°)	1.51	1.43	1.38
Extension (°)	3.30	3.62	5.51
Flexion (°)	2.34	2.62	4.45
Hip ROM (°)	12.5	9.25	27.5
Hip Abd/Add (°)	14.2	12.5	16.1
Hip Rotation (°)	33.5	27.6	25.2
RMS Angular Velocity ($°/s$)	1.52	1.31	1.00
RMS Angular Acceleration ($°/s^2$)	45.5	43.7	37.7
RMS Jerk ($°/s^3$)	1.07E+03	1.05E+03	998

4.5 Discussion

Error between IMU sensor metrics and ground truth motion capture metrics, comparison to the effect size, and discussion of feasibility of remote monitoring was presented in Chapter 4. Error varies between exercise, collection days, and limbs. Validation of the algorithms on healthy subject data sets reported average errors of ≈6.47° in sagittal plane movements [7] and 5.73° in the sagittal knee joint and ≈34.3° and ≈15.52 ° across hip and ankle joints respectively (spherical cumulative of 3 joints) during squats [55]. This case study highlights the variability of error, where mean error for some metrics were below average reported errors and others higher. Error in commonly used recovery metrics for the heel slide were larger than reported values although still lower than the effect size in the affected limb over recovery. Whereas the error for commonly use metrics for the leg raise exercise were lower than reported values, the changes over recovery were smaller than the average error. The use of this algorithm remotely is dependant on the metrics being assessed and further work to improve the metric accuracy across a wider range of exercises.

ROM errors in this work can be compared to published joint angle errors for an indication of performance, however published values are errors between entire joint trajectories whereas error discussed in this section are differences between ROM measurements. This work also examines a patient population compared to a healthy population and one case study instead of a large subject pool. The variability in error between collections, whether it is different legs, days, or exercises, displays a lack of consistency in sensor based metrics or a greater need for more specific algorithm tuning. Given more data, future work might benefit from statistical analysis of which factors have the largest effect on error to potentially incorporate this into the algorithm design.

The IMU algorithm was not modified between exercises or days, motivating an initial exploration of EKF tuning by exercise. Data from tuning the EKF observation noise parameters based on individual exercise was described and reported. Results indicate that changing the gyroscope observation noise differently for the heel slide and leg raise generate lower errors in the recovery metric reconstructions compared to motion capture ground truth. This highlights the importance of noise parameter selection in accurate reconstruction for remote monitoring of exercises. Changing the observation noise covariance decreased the error in knee joint range of motion by 3.49° during the heel slide. When measuring increases per day in the range of 4° to 10°, decreasing the error by this magnitude becomes important.

In an ideal case, the EKF algorithm would initially be tuned to generate a better reconstruction than what was originally used in this case study. However, results from this process provide good indication that changing filter parameters based on exercise may result in a more accurate reconstruction. Results also show error between ground truth and sensor-based metrics may rely heavily on the choice of not only the process noise, but also the measurement noise. Future work could expand on the exercise specific tuning of the process noise variables in the EKF algorithm to determine the ideal setting for each exercise. An individualized tuning method would required a larger collection of subjects for each exercise, which may be inefficient at scale and would need to be tested further to determine the effectiveness. In this study, conducted in a research laboratory, initial placement of IMU sensors was confirmed using motion capture markers. In a clinical or remote application, where motion capture is unavailable, the initial position of the IMUs would not be confirmed using this method. Without motion capture, the initial position could be set with an initial known pose. However, errors associated with misplacement were not investigated in this work.

Chapter 5

Clinician Survey

5.1 Introduction

In this chapter, clinical expertise is surveyed to acquire feedback on the metrics explored in the case study. While a practicing therapist provided regular feedback throughout the thesis project, the varying nature of clinical expertise makes it difficult to have one source of information to pull from. A survey was designed and distributed to gather clinician feedback on selected recovery metrics, the impact these recovery metrics would have on rehabilitation practice, and if/how they would use the data a remote monitoring tool would provide.

5.2 Methods

The survey was distributed primarily via the Canadian Association of Physiotherapy (Orthopedic Division) newsletter and Physical Therapy departments at Dalhousie University, University of Toronto, and McMaster University. Personal connections through word of mouth and professional networks were also invited to participate in the survey. This study was reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB 44058).

The layout of the survey was as follows:

1. Information and Consent Form
2. Introduction

3. Case Study Information
4. Feedback on Results
5. Gathering Clinician Information
6. Rehabilitation Protocol

In the online survey, results from phase A and B of recovery were consolidated. Plots of selected recovery metrics over time were presented as plots. Metrics included were:

- Supine Single Leg Heel Slide
    1. Knee range of motion
    2. RMS angular velocity
    3. Extension/flexion time ratio
- Supine Straight Leg Raise
    1. Knee range of motion
    2. Repetition time
- Overground Straight Line Walking
    1. Average step length
    2. Average step width
    3. Step length asymmetry
    4. Step width asymmetry

The metrics were presented by exercise, with an introduction to each exercise including a link to a representative video. Metrics were described and the plots explained in a preamble before the data were presented. An example of data presented in the survey is shown in the plot in Figure 5.1.

After metrics were presented in form of plots showing average metric values over recovery (similar to those presented in Ch 3), the following questions were presented. The same questions were asked for each metric (indicated by 'METRIC X' below). Question 3 was displayed if the participant responded YES to question 1 and question 4 was displayed if the participant responded NO.

- **Question 1:** When treating a patient recovering from a partial meniscectomy, do you evaluate METRIC X during EXERCISE Y as an indicator of recovery?
- **Question 2:** If yes, how do you currently evaluate METRIC X? If no, why not?
- **Question 3:** Would you consider using the data in Figure X to assess METRIC X progression instead of or in conjunction with your current method of assessing METRIC X progression?
- **Question 4:** If this data, showing METRIC X progression over the recovery period, was available to you, would you use it to help inform your therapeutic decision making? And why?

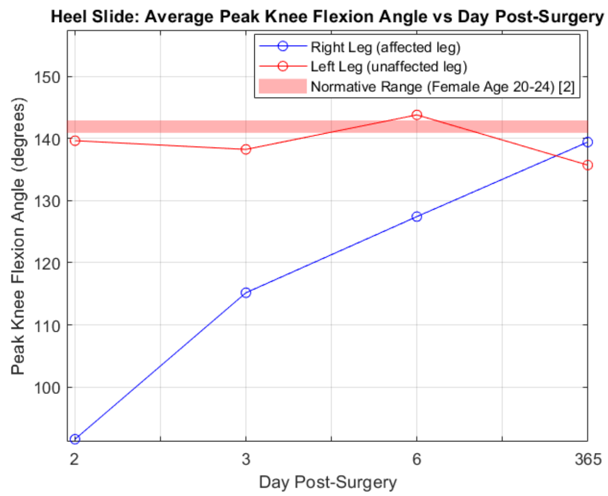

Figure 5.1: Example of metrics data used in the clinician survey to gather feedback on recovery metrics. Plot shows peak knee angular deviation, referred to as knee sagittal plane ROM in this work, over recovery for the affected and unaffected limbs and with motion capture data.

At the end of each exercise section, participants were asked whether the information provided a similar decision as the therapist in the case study to progress the recovery protocol at the same stage. They were also asked if there were additional metrics for each exercise that they would use to assess the exercise and how they evaluate additional metrics. Closed-ended survey questions were assessed quantitatively and a preliminary qualitative analysis of open-ended questions was performed. Written feedback was summarized and paraphrased in the points provided.

Nineteen participants responded to the survey. The survey received six complete responses, seven responses for the heel slide and walking results only, four responses giving feedback on the heel slide section only, one response giving feedback on the heel slide and leg raise results sections, and one response giving feedback on all three exercise results sections. All participants that provided their job title (14/19) were physiotherapists with orthopedics as primary field of care. Other fields of care included neurology, sports physiotherapy, return to work, pelvic floor rehabilitation, and geriatric care. Respondents mean years working was 8.67 +- 4.71 year. Nine participants provided conservative treatment to meniscal tear patients weekly, three participants monthly, and two participants provided treatment once very 2-3 months. Three participants provided care after APM surgery weekly in their work, two participants regularly provided care monthly, five provided care every 2-3 months, and four provided care approximately every six months. The primary demographic of the patients that the respondents treated after APM surgery was the general public.

5.3 Results

Figure 5.2 summarizes the responses for Question 1, asking if the respondent typically evaluates the metric during recovery after an APM procedure, where the y-axis is the number of responses of 'Yes' and 'No' for metrics listed on the x-axis. Knee ROM during heel slide and leg raise, and step length were considered to be the commonly used metrics. 78.0% of survey participants said they evaluate these common metrics post-APM. Knee ROM during leg raise was the least evaluated metric (4/8 responding 'Yes'). Instead, quadriceps strength was commonly evaluated though visual observation. For the remaining exploratory metrics, 21.6% of clinicians said they already assess these metrics in clinic, usually through subjective visual observation.

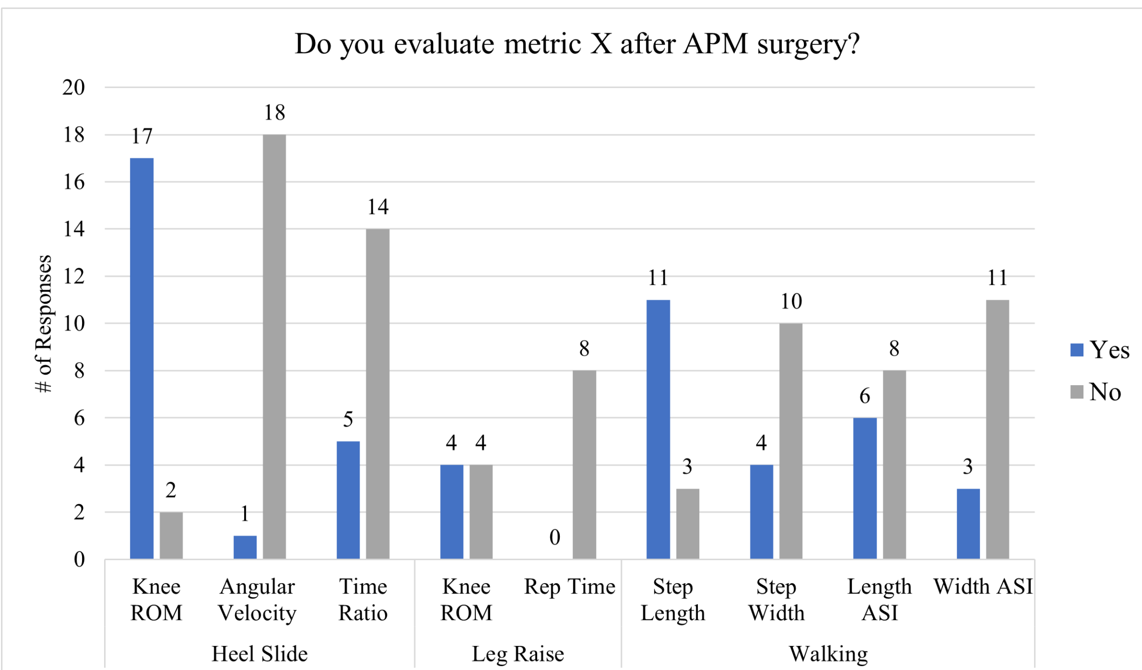

Figure 5.2: Summary of responses for survey Question 1 for all exercises and metrics.

5.3.1 Heel Slide

Table 5.1 lists the responses for Question 1 for the heel slide exercise, including written feedback. All written feedback for this question was summarized in the points provided. The 17 survey respondents indicating they evaluate knee ROM during the heel slide assessed visually, based on feel, or using a goniometer. While one participant indicated they evaluate angular velocity visually, 18 of 19 respondents said they do not have the tools to measure this. One participant reported velocity was not important in early phase of recovery. The participants who stated they evaluate extension/flexion time ratio, do so through visual observation.

Table 5.1: Responses for Question 1 of the Survey for Heel Slide Metrics and Written Responses from Participants

Exercise	**Metric**	**Do you evaluate X after APM surgery? (# of responses/total)**	**If yes, how do you evaluate? If no, why?**
Heel Slide	Knee ROM	Yes, how? (18/19)	• Visually • Based on feel • Goniometer
		No, why? (1/19)	• Not usually limited
	RMS Angular Velocity	Yes, how? (1/19)	• Observation
		No, why? (18/19)	• Can't measure • Not important in early phase
	Extension/Flexion Time Ratio	Yes, how? (5/19)	• Visual observation
		No, why? (14/19)	• No tools to measure

Figure 5.3 shows the responses for Question 3 of the survey. Question 3 was displayed to participants when they answered that they use the recovery metric presented. 70% of clinicians responded and said they would use the data provided to assess the recovery metric with their current methods as well. Only 4% of responses indicated that they would not use the data provided. Figure 5.4 shows responses for Question 4 of the survey.

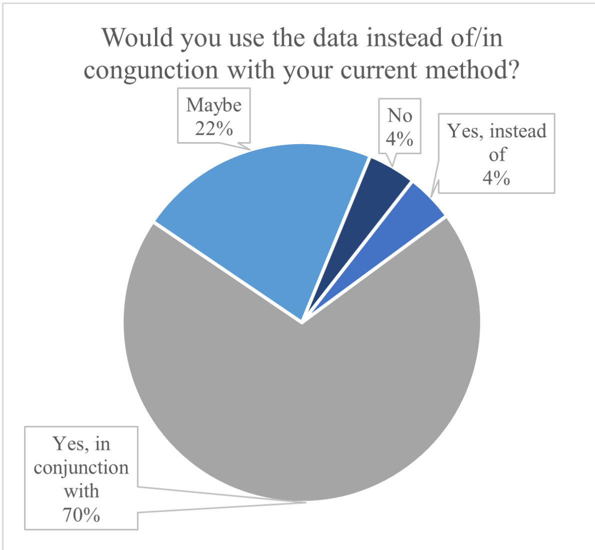

Figure 5.3: Responses for Question 3 of the survey for more common heel slide metrics.

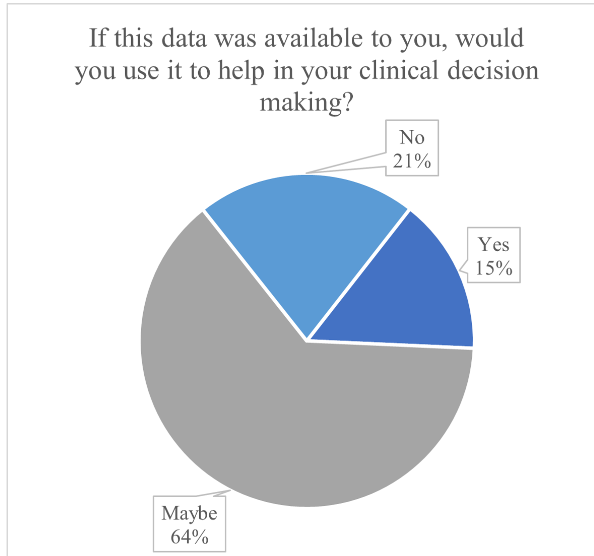

Figure 5.4: Responses for Question 4 of the survey for exploratory heel slide metrics.

When respondents did not use the presented metric, they were asked if they would consider the metric to help inform their clinical decision making, if it was available. 15% of the participants responded 'yes' and 64% responded 'maybe'. Some comments on potentially using exploratory metrics included:

- "it [angular velocity] may comment on the quality of movement - e.g. faster, smoother leg slide"
- "It would help show not only the amount of movement, but the willingness to move more quickly, which can be a helpful indicator on recovery to pain free/willing movement and ultimately return to sport"
- "It is a more objective measure of the patients quality of movement"
- "[extension/flexion time ratio] seems to give a good indication of recovery"

The clinicians were asked if they agreed with the therapists decision to progress therapy at day 6 based off the information provided in the survey. The answers were split with seven responses agreeing with the decision and six responses disagreeing with the decision. Providing this data to the therapist at the time of recovery may have changed the therapeutic decision making. The primary metric that participants in the survey would also assess was knee extension angle during the heel slide. Knee extension angle during the heel slide was also measured as a recovery metric and presented in Chapter 3.

5.3.2 Walking

Table 5.2 lists the responses for Question 1 for the survey for only overground walking metrics along with the written feedback. All respondents who measure step length, width, step length asymmetry index, and step width asymmetry index assess these metrics visually. The majority of participants do not measure asymmetry metrics and the most common response was they have no tools to measure this or it was too complex and there is limited time.

Table 5.2: Responses for Question 1 of the Survey for Overground Walking Metrics and Written Responses from Participants

Exercise	**Metric**	**Do you evaluate X after APM surgery? (# of responses/total)**	**If yes, how do you evaluate? If no, why?**
Overground Walking	Step Length	Yes, how? (11/14)	• Visual inspection
		No, why? (3/14)	
	Step Width	Yes, how? (7/14)	• Visual inspection
		No, why? (7/14)	
	Step Length Asymmetry Index	Yes, how? (6/14)	• Visual Inspection
		No, why? (8/14)	• Do not have the tools to measure • Limited time
	Step Width Asymmetry Index	Yes, how? (3/14)	• Visual Inspection
		No, why? (11/14)	• No tools • Too complex

Figure 5.5 shows the responses for Question 3 which focused on walking. Sixty-five percent (65%) of clinicians responded, indicating they would use the data provided to assess the recovery metric with their current methods as well and 17% said they would use the data instead of their current method. Only 6% of responses (1 participant) indicated that they would not use the data provided. Figure 5.6 shows responses for Question 4 of the survey for walking. Thirsty-six percent (36%) of the participants responded 'yes' they would use the data to assess these metrics that they do not currently assess and 55% responded they would 'maybe' use the data if it were provided to them during recovery.

- "[I would use the data] provided the time and cost was reasonable"
- "it [step length and width data] would provide an objective measure of recovery"

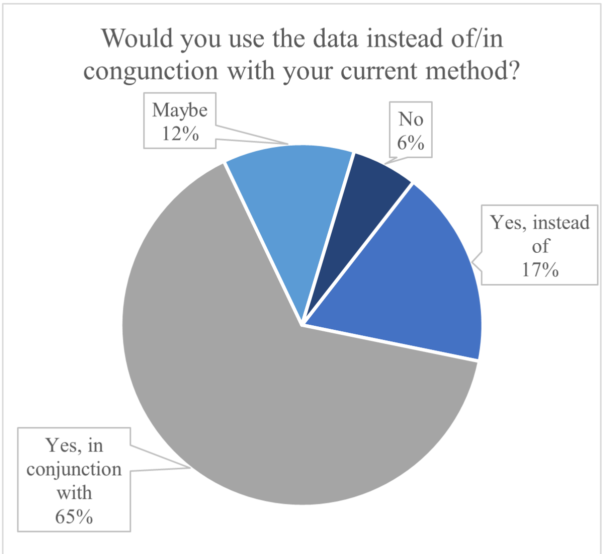

Figure 5.5: Responses for Question 3 of the survey for more common walking metrics.

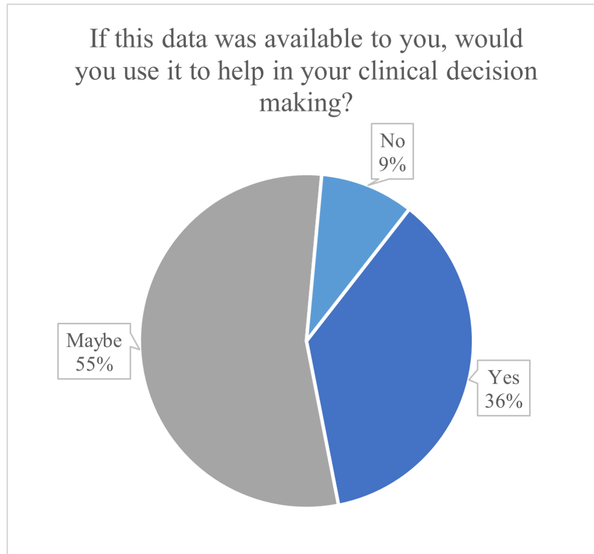

Figure 5.6: Responses for Question 4 of the survey for the exploratory walking metrics.

Step length and width asymmetry were used in clinic by 3 of 14 respondents, step length asymmetry only was used by 3 of the respondents, and the other 8 indicated that they do not evaluate step length or width asymmetry. If participants did assess these metrics they assessed through visual assessment of gait. Reasons for not assessing these metrics are primarily due to lack of measurement resources and limited time for re-measurement to assess recovery. Six participants said they would use this data if it was made available to them and 1 participant said they would probably not use this data because step length and width are a sufficient source of data to assess recovery.

Additional metrics that the participants assess during gait were walking speed, "distance before problematic gait", strength of gastrocnemius/soleus, "step ease", knee range of motion during swing phase, and weight bearing asymmetry based on observation. Several other metrics described in Chapter 3 may fit a few of the suggested metrics. Knee ROM was assessed using this tool (see Figure 3.3 and step time could potentially indicate 'step ease'. Overall, 13 (of 14) respondent said that having this data from collections at home would potentially be helpful when treating patients.

5.3.3 Leg Raise

Table 5.3 lists the responses for Question 1 for leg raise metrics, along with the written feedback from participants. Of the 8 participants that provided feedback on the leg raise exercise, 4 responded they do not evaluate knee ROM either due to lack of measurement devices or ROM does not need to be measured and naturally improves over time as quad strength improves. Four said they do assess this metric as an ”objective measure of exercise performance”, by observation, or with a goniometer.

Table 5.3: Responses for Question 1 of the Survey for Leg Raise Metrics and Written Responses from Participants

Exercise	**Metric**	**Do you evaluate X after APM surgery? (# of responses/total)**	**If yes, how do you evaluate? If no, why?**
Leg Raise	Knee ROM	Yes, how? (4/8)	• Visually • Goniometer • ‘Objective measure of exercise performance’
		No, why? (4/8)	• No tools for measurement
	Repetition Time	Yes, how? (0/8)	
		No, why? (8/8)	• Can’t measure • Would be subjective

All participants that currently use knee ROM in their practice responded they would use the data provided, if available to them, to help inform their decision making. Figure 5.7 shows responses for survey Question 4 for leg raise metrics. All participants stated that they do not formally assess repetition time, but would use the data if provided. Of the clinicians who did not use knee ROM or repetition time as metrics for the leg raise, 27% of survey participants said they would use the data provided to inform their clinical decision making. Fifty-five percent (55%) of participants who do not currently use knee ROM or repetition time said they would potentially use the data to help inform their clinical decision making. Only 1 participant (18%) said they would not use the data provided to inform treatment.

Responses were also split regarding the decision to eliminate the leg raise on day 6. Four respondents agreed, and 3 did not agree or were unsure. Other metrics clinicians reported using for the leg raise were pain reports from the patient, number of repetitions performed before fatigue, and ability to bear weight.

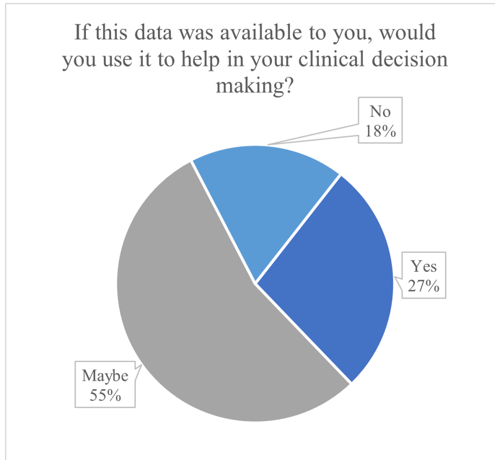

Figure 5.7: Responses for Question 4 of the survey for exploratory leg raise metrics.

5.4 Discussion and Conclusions

The purpose of the survey was to gather feedback from clinicians to inform decision behind exploratory recovery metrics, objective measurement of existing and exploratory metrics, and gauge future uptake of metric data. Considering clinicians are the primary target users in this work, it was important to understand what is important in recovery and whether the information is useful to inform decision-making. Although guidelines exist around therapy protocols for different procedures [15], [32], each protocol varies in exercises and metrics depending on clinician preference, as demonstrated by this survey. The range of results from Question 1 for the leg raise knee ROM provides interesting insight on the variability in care and theory in the physiotherapy community. Some therapists say they do not have the tools to measure knee range of motion, while others use a goniometer and/or operate purely on observation based methods. All 4 participants who assess knee ROM also indicated they would use the data provided in conjunction with their current method. This highlights the importance of gathering clinician feedback as an indicator of current methods to inform acceptance into the community.

The objective of this tool is to provide this data to clinicians, including remotely, to monitor progress every day (the patient performed exercises). A reported reason for not measuring data included limited time, which may be mitigated by acquiring performance data every day (exercises were done). The primary feedback received was that clinicians lack the tools necessary to measure metrics, but would use the data if it were provided. This tool provides the data clinicians need to use the metrics.

Over all metrics presented, 95.5 % of respondents said they would use the data if it were available to them to help them assess metrics tat they already assess in clinic. For metrics that clinicians said they did not use, 81.1 % of respondents said they were open to using the information to help inform therapeutic decision making. Additionally, 92.9 % of survey respondents indicated information about rehabilitation exercise performance at home would be beneficial when treating patients. Survey results provide good indication that given accurate data and logistic constraints like time and cost are met, the information this tool can provide would be accepted and used by clinicians in clinic and at-home settings to inform therapeutic decision making. A limitation of this work was that at-home and clinic feasibility was not assessed by clinicians in this survey.

Chapter 6

Conclusion

This work presents a case study for examining existing and exploratory recovery metrics during lower limb physical therapy and the application of remote monitoring using the metrics generated from IMU data. Physiotherapy after injury or procedure is important to regain function, mobility, strength, and endurance. Clinicians typically use visual or goniometric measurements for in-person kinematic assessments and manual muscle testing for strength assessments. Objective measurement tools, such as motion capture, force plates, Biodex testing, are costly, bulky, and not time effective. While patients see clinicians for exercise prescription and assessment, the bulk of recovery takes place when doing rehabilitation exercises at home. In many cases, access to in person physiotherapy may be limited or non-existent because of regional and demographic differences. Small, wearable IMUs that reconstruct 3D human motion digitally can be used remotely, in clinic and/or at home, to visualize the motion and generate metrics to assess recovery remotely.

Table 6.1 lists the recovery metrics for the five exercises examined in this thesis. Metrics highlighted in blue are exploratory, and non-shaded metrics represent existing metrics. Metrics are ranked as strong, moderate, or weak in three categories, showing recovery (Ch 3), feasibility of IMUs to measure recovery (Ch 4), and feedback from clinicians (Ch 5). Metrics showed strong evidence of recovery (Ch 3) if all of the following conditions were observed: improving trends over the recovery period, trends between affected and unaffected limbs, and significant differences. Metrics showed moderate evidence of recovery if two of three conditions were met and weak evidence of recovery if only one or no conditions were met. IMU feasibility (Ch 4) was rated based on error between IMU and motion capture metrics being smaller than the effect size and IMU metrics demonstrating similar recovery trends to motion capture metrics. IMU feasibility was considered strong if both these conditions were met, moderate if only one condition was met, and weak if neither

Table 6.1: Metric Summary

Exercise	Metric	Chapter 3 - Recovery	Chapter 4 - IMU Feasibility	Chapter 5 - Feedback
Heel Slide	ROM	Strong	Strong	Strong
	Extension	Moderate	Moderate	-
	RMS Angular Velocity	Strong	Strong	Strong
	RMS Angular Acceleration	Strong	Strong	-
	Repetition Time	Strong	Strong	-
	Extension-Fexion Time Ratio	Moderate	Moderate	Strong
Leg Raise	ROM	Weak	Moderate	Strong
	Extension	Moderate	Moderate	-
	Flexion	Moderate	Moderate	-
	Hip ROM	Moderate	Moderate	-
	Hip Abd/Add	Moderate	Weak	-
	Hip Rotation	Moderate	Weak	-
	Max Knee Angle	Weak	Moderate	-
	Time of Max Angle	Weak	Moderate	-
	RMS Angular Velocity	Moderate	Moderate	-
	RMS Angular Acceleration	Moderate	Weak	-
	RMS Jerk	Moderate	Weak	-
	Repetition Time	Strong	Strong	Moderate
	Extension/Flexion Time Ratio	Weak	Strong	-
	Time Offset	Moderate	Moderate	-
Walking	Hip ROM	Moderate	Moderate	-
	Hip Abd/Add	Moderate	Weak	-
	Ankle ROM	Weak	Weak	-
	Knee ROM	Strong	Weak	-
	Step Time	Strong	Moderate	-
	Step Length	Strong	Weak	Strong
	Step Width	Strong	-	Strong
	Step Length Assymetry Index	Strong	Weak	Strong
	Step Width Assymetry Index	Strong	-	Strong
Goblet Squat	Hip ROM	Strong	Moderate	-
	Hip Abd/Add	Strong	Moderate	-
	Hip Rotation	Moderate	Weak	-
	Ankle ROM	Strong	Moderate	-
	Knee ROM	Strong	Moderate	-
	Knee RMS Angular Velocity	Strong	Strong	-
	Time Ratio	Weak	Weak	-
	Repetition Time	Moderate	Strong	-
RDL	Moving ROM	Strong	Strong	-
	Moving Abd/Add	Weak	Moderate	-
	Moving Int/Ext Rotation	Weak	Moderate	-
	Moving Ankle ROM	Moderate	Moderate	-
	Moving Knee ROM	Moderate	Strong	-
	Moving Knee RMS Angular Velocity	Moderate	Strong	-
	Stationary ROM	Strong	Moderate	-
	Stationary Abd/Add	Weak*	Moderate	-
	Stationary Int/Ext Rotation	Strong	Moderate	-
	Stationary Ankle ROM	Strong	Moderate	-
	Stationary Knee ROM	Moderate	Moderate	-
	Stationary Knee RMS Angular Velocity	Moderate	Strong	-
	Repetition Time	Moderate	Strong	
	Time Ratio	Moderate	Strong	

condition was met. Strength of clinician feedback from the survey (Ch 5) was based on the percentage of responses that said they would potentially use the data to inform therapeutic decision making. Feedback was considered strong if the percentage of favorable responses was greater than 60%, moderate if the percentage of responses was 40-60%, and weak if it was less than 40%. Metrics that track recovery in the case study, have good IMU feasibility, and have positive feedback from clinicians are highlighted in green. Metrics with good potential in one category and need improvement in other categories are shaded in yellow, and metrics that do not track recovery or have good IMU feasibility are colored in red. Overall, 10 metrics are rated as strong in all three or two (in cases where clinician feedback is not available) categories, where tracking recovery could be implemented remotely to monitor recover using current algorithms. Six (6) other metrics were tracked well using the IMU metrics, however did not show recovery in this case study. Given more data or different procedures these metrics may be demonstrably useful rehabilitation metrics. Ten (10) metrics showed trends over the recovery period, but only demonstrated moderate success tracking trends using IMUs. To use these metrics in a remote manner, future work is needed to advance algorithm performance.

Chapter 3 discusses current practice and shows potential for new recovery metrics to assist in monitoring recovery. Five physiotherapy exercises were analyzed over a 15 day recovery period. Current metrics show recovery over time and highlight where deficits exist between end of recovery values and the healthy baseline one year post-surgery. Exploratory metrics include rate-based metrics like angular velocity and jerk, temporal ratios comparing antagonist movements, and trends in data. Novel metrics show improvement or increase over time in the affected leg and deficits between the affected and unaffected limbs in single limb exercises. These metrics, such as angular velocity in the affected joint and extension-flexion time ratio show potential for measuring recovery and providing more information in a remote setting where visual assessment is not possible.

Chapter 4 compares the error between IMU and motion capture metrics to the effect size over recovery and results from exercise specific tuning of EKF noise parameters. The goals of this chapter were to examine the potential for remote monitoring and how changing noise parameters affects reconstruction of recovery metrics. In many cases, effect size over recovery is larger than sensor-based metric error and trends in sensor metrics accurately reflect trends in ground truth metrics over time. Effect size between the unaffected limb and affected limb was not always larger than the error in metrics. Although the same algorithm was used for all data processing, error varied between exercise, day, and even limb. The EKF noise parameters were tuned for the heel slide exercise first, with the same tuning parameters applied for leg raise. In general, increasing the gyroscope observation noise decreased the metric error for heel slide, while decreasing the gyroscope noise decreased metric error for leg raise. Preliminary results for exercise-specific tuning of EKF noise parameters indicate that finding optimal values for each exercise might improve the quality and potential for remote monitoring using a wearable mobile IMU system.

Chapter 5 presents results from a clinician survey that gathered feedback on using objective data from existing recovery metrics, the future uptake of novel recovery metrics without consideration of collection logistics, and case study clinical decision making. Nineteen (19) physiotherapists participated in the survey. Over all metrics, 95.5% of participants responded they would use data to help their clinical decision making, and 81.1% indicated they would use data from exploratory recovery metrics, if available. Survey results demonstrated that clinicians would be willing to use the recovery metric data and exploratory metric data would be used in clinic.

This work is limited to one case study patient and should be expanded to a larger participant set. The subject pool should be subjects presenting with the same injury and receiving the same treatment and therapy protocol. Additional subjects should also be athletes to properly compare to this case study. Future work beyond this point could expand to different demographics and patients with different lower limb injuries or surgeries. Participant recruitment was limited by access to patients with similar procedure and COVID-19 restrictions. Clinical validation of all recovery metrics and exploratory metrics with statistical significance requires more participants with varied demographics. Because only one subject was collected, the current statistical analysis is limited. The data does not meet to the requirement of independent observations required for a t-test. Future work should expand the participant pool to verify findings. A verification study with the addition of EMG data collection could be included to further validate findings relating kinematic data to activation. Additional participants could expand this work to use data driven methods, such as machine learning classification tools, to label participants as recovered or not recovered and further aid therapists in performing remote monitoring. Additional metrics could be generated using data driven methods where frequency spectrum metrics might provide more information for remote monitoring and metrics based on pattern recognition not available using current methods. This work would benefit from integration of metric extraction with automatic repetition detection and gait cycle detection algorithms to create a well rounded product for recovery monitoring.

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APPENDICES

Appendix A

Additional Metrics for Supine Single Leg Raise

The following recovery metrics for supine single leg raise were presented in the appendices for brevity and/or due to lack of demonstrating recovery. Metric t-test results are located in Table 3.5. Error between IMU metrics and motion capture metrics are located in Table 4.3 and effect size compared to error in Table 4.4.

A.1 Hip ROM

Figure A.1: Hip ROM in the frontal plane, corresponding to hip abduction/adduction, was consistently larger on the affected leg. While this finding may not be highly relevant for the APM procedure this case study focuses on, however, out-of-plane hip ROM may indicate other imbalances. Hip frontal ROM showed significant differences between the affected and unaffected legs, and between the affected leg on different days.

Figure A.2: Hip transverse plane movement (i.e., internal and external rotation) was negative on the left leg and positive on the right leg on day 2 post-surgery, where positive values indicate external rotation. On day 3 and 6, a sign reversal was observed, however the magnitude was smaller. The left leg had on average of -3.85° of rotation on day 3 and -1.34° rotation on day 6 and the right leg had on average of 0.117° of rotation on day 3 and 1.26° rotation on day 6. Hip transverse ROM showed significant differences between the affected and unaffected legs, and between the affected leg on different days.

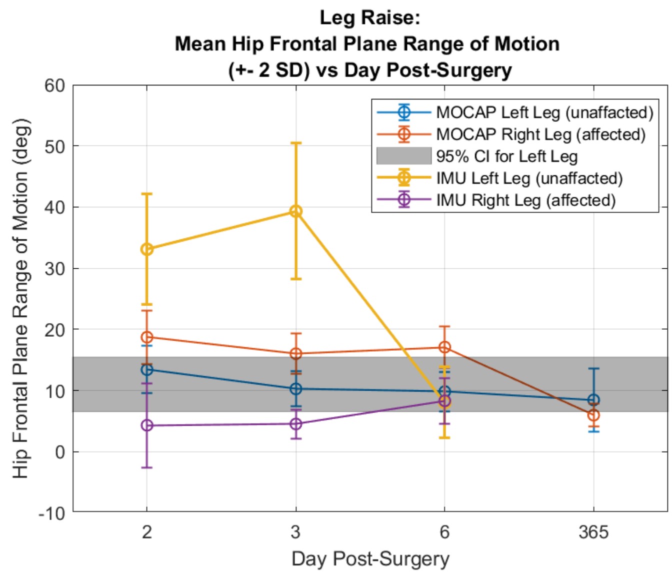

Figure A.1: Frontal plane (abd/adduction) hip range of motion for single leg raise on each day of recovery (±2SD).

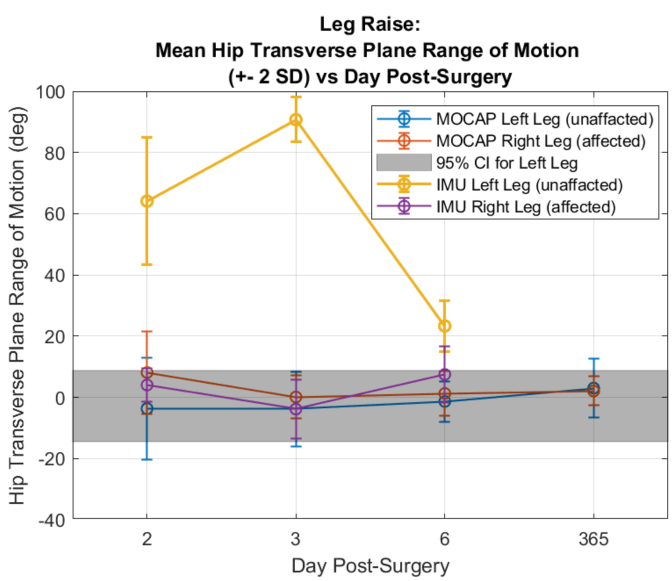

Figure A.2: Transverse plane (internal/external rotation) hip range of motion on each day of recovery (±2SD).

A.2 Knee Sagittal Plane RMS Angular Velocity and Acceleration

RMS angular velocity and RMS angular acceleration were extracted for the knee joint. Considering the instructions is to keep the knee straight during leg raise, lower angular rates of motion in the knee joint are desired.

Figure A.3: shows the RMS angular velocity of the knee joint for the affected and unaffected legs. The affected leg had lower RMS angular velocity than the unaffected legs on all days post-surgery. One year post-surgery both these metrics were nearly identical. On day 2, the affected leg RMS angular velocity was $1.38°/s$ lower than the unaffected. While the unaffected leg remains relatively constant over day 3 and 6, the affected leg RMS angular velocity decreases. The difference between legs increases to $4.35°/s$ on day 3 post-surgery and $1.68°/s$ on day 6 post-surgery.

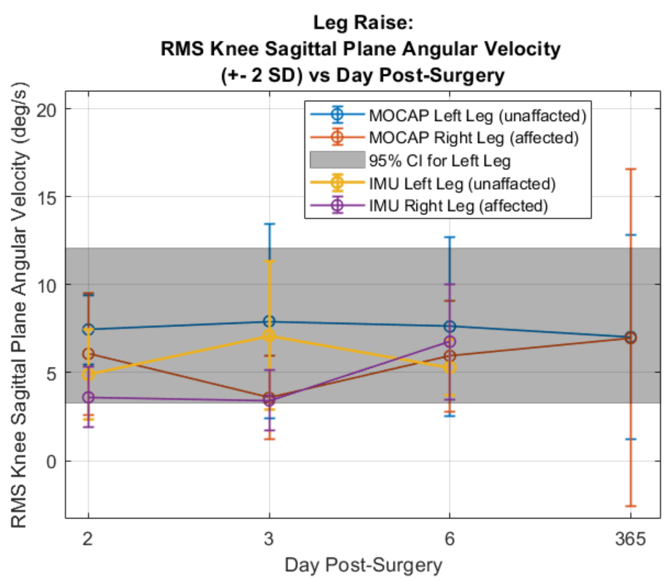

Figure A.3: Mean knee RMS angular velocity on each day of recovery for the leg raise (±2SD).

Figure A.4: shows the RMS angular acceleration of the knee joint for the affected and unaffected legs. The affected leg had lower RMS angular acceleration than the unaffected legs on all days post-surgery. One year post-surgery both these metrics were nearly identical.

Comparing affected and unaffected legs, RMS angular acceleration shows a similar trend to velocity. The unaffected leg trends upwards over recovery, whereas the affected leg fluctuates between days. Observations for the affected leg fall within 2 SD of the unaffected leg movements. Due to high variance and lack of consistent performance across the recovery period, RMS angular velocity and acceleration in the knee may not be useful metrics to show recovery for the leg raise. However, a noteworthy finding was RMS angular velocity and acceleration at one-year post-surgery the affected and unaffected legs demonstrated similar performance, potentially indicating utility as a recovery metric.

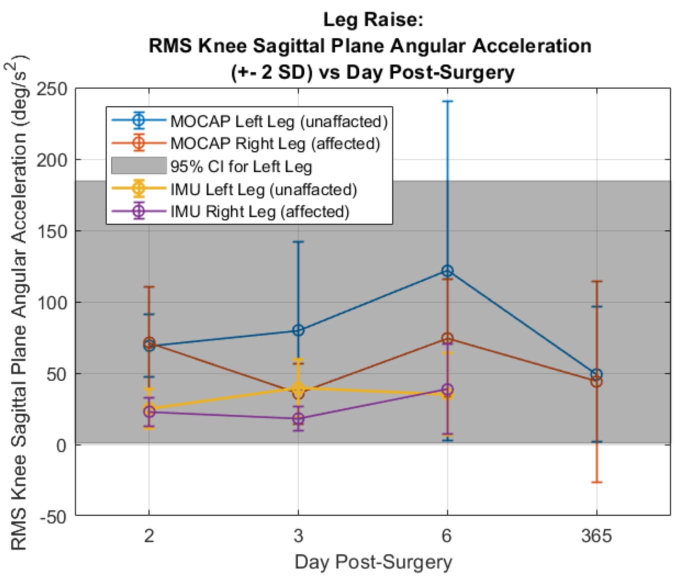

Figure A.4: Mean knee RMS angular acceleration on each day of recovery for the leg raise ($\pm$2SD).

RMS angular velocity and acceleration for the knee joint show no significant improvements over the course of recovery or between the two legs, although we do see changes in magnitude of these metrics and discussed their importance when presenting the data plots. One finding in both metrics was that the difference between legs one year post-surgery was much smaller than the difference between limbs over recovery. If this were a consistent finding given more data, than there could be a greater importance in the difference between legs during rehabilitation periods.

A.3 Repetition Time

Mean repetition time for the leg raise exercises is presented in A.5. Mean repetition time for the leg raise on the affected leg decreased from 3.78±1.60s on Day 2 post-surgery to 2.57±0.937s on Day 6 post-surgery (-1.21s). On Day 6, the affected leg performed within the 95% confidence interval of the unaffected leg. Variance of the repetition time consistently decreased from day 2 to 6 on the affected leg, while remaining similar on all days for the unaffected leg. Similar to repetition time for the heel slide, this metric could provide early indications of strength recovery in the affected leg, while it is not commonly assessed by clinicians especially in early stages of recovery.

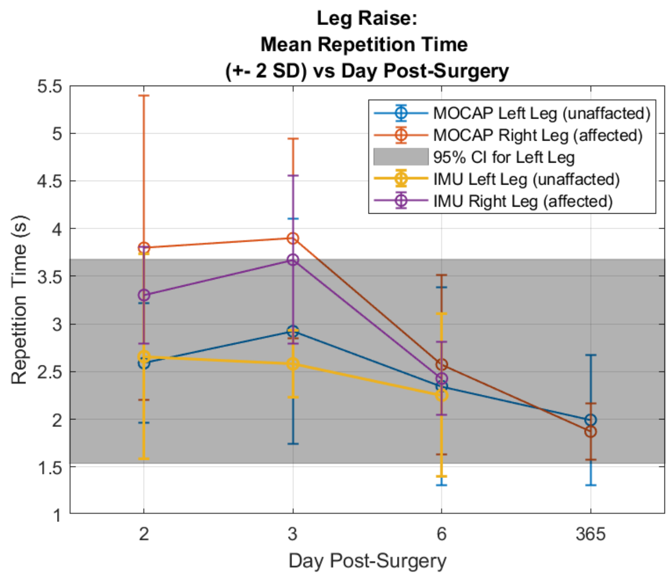

Figure A.5: Mean repetition time on each day of recovery for the single leg raise (±2SD).

Mean repetition time was significantly smaller on the unaffected side on day 2, and no difference was observed between the unaffected and affected sides on day 6. Repetition time also improved significantly from day 2 to day 6 on the affected leg.

A.4 Time Ratio

Figure A.6: The up-down time ratio was the time to reach the midpoint of the exercise action divided by the time from midpoint to the end of the exercise repetition.

A.5 Maximum Angular Deviation

Figure A.7: The maximum angular deviation during each repetition was a variation of

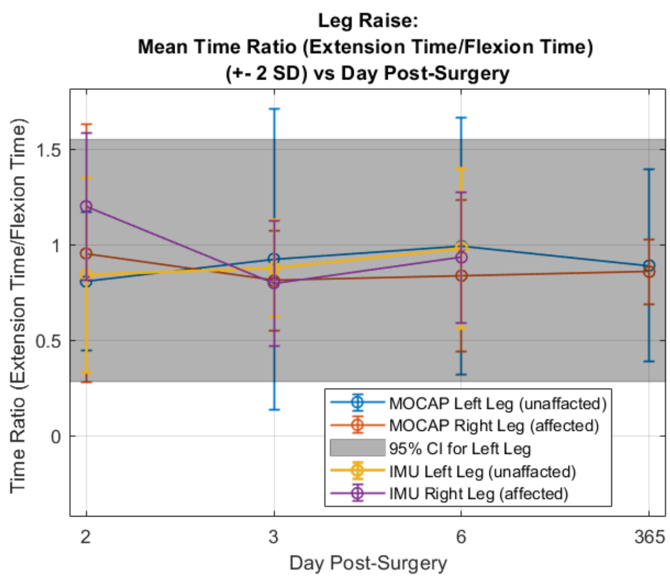

Figure A.6: Ratio of time up (hip flexion) and time down (hip extension) on each day post-surgery (±2SD).

finding knee ROM and max knee angles. Knee motion was small and variable in knee joint angle trajectories during the leg raise. There were not always clear flexion and extension points during one repetition of the exercise. This metric found the maximum magnitude of absolute angular deviation and reported the signed value for that repetition.

A.6 Normalized Time

Figure A.8: The normalized time of maximum angular deviation was the time after the start of the repetition that maximum angular deviation occurs divided by the total repetition time.

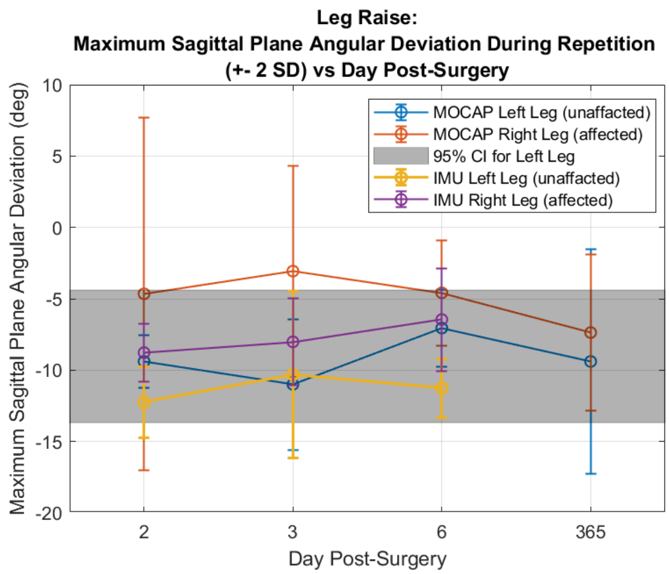

Figure A.7: Maximum angular deviation during repetition (either flexion or extension) for each day post-surgery (±2SD).

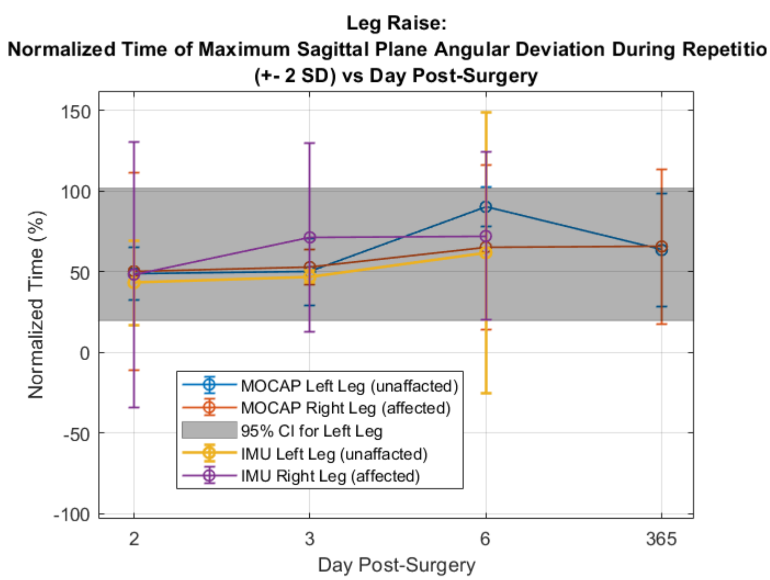

Figure A.8: Time of maximum angular deviation (Figure A.7) normalized by total repetition time (±2SD).

Appendix B

Additional Metrics for Goblet Squat

The following recovery metrics for the double leg goblet squat were presented in the appendices for brevity and/or due to lack of demonstrating recovery. Metric t-test results are located in Table 3.9. Error between IMU metrics and motion capture metrics are located in Table 4.7 and effect size compared to error in Table 4.8.

B.1 Hip Internal/External Rotation

Figure B.1: Hip transverse plane ROM corresponding to internal and external rotation. Where internal rotation is negative and external rotation is positive.

B.2 Repetition Time

Figure B.2: Average repetition time over recovery. A decreasing trend was observed during recovery, however one year post-op repetition time was similar to times at the start of recovery. The first day squat was collected was also day 7, one week after the surgery and functional range of motion was recovered. The subject may have been comfortable performing squats already. For other exercises the decrease in repetition time is also greater, indicating more of a change over recovery in ease of motion or comfort.

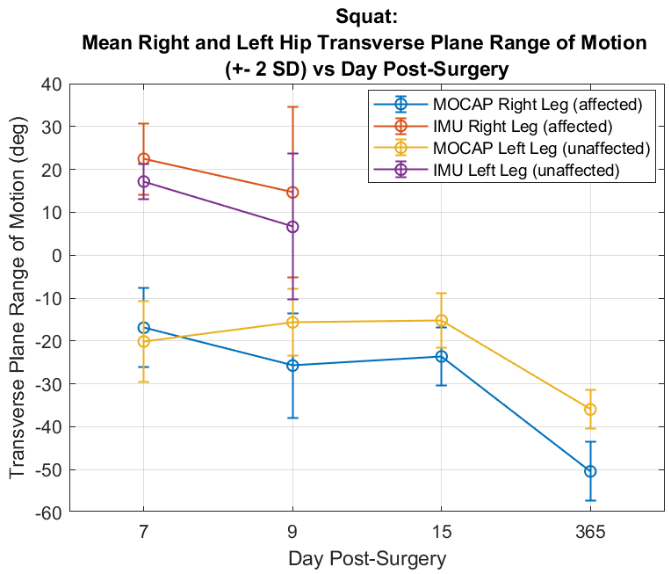

Figure B.1: Mean hip transverse plane range of motion during double leg goblet squat (±2SD).

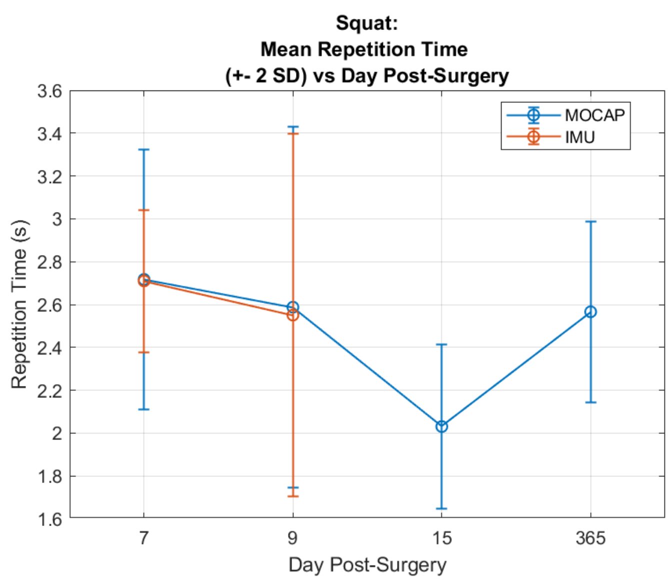

Figure B.2: Mean repetition during double leg goblet squat (±2SD).

B.3 Extension/Flexion Time Ratio

Figure B.3: The extension to flexion time ratio is a ratio between the time from the bottom of the squat to the end position and the time from the start position to the bottom of the squat (max hip, knee, and ankle flexion).

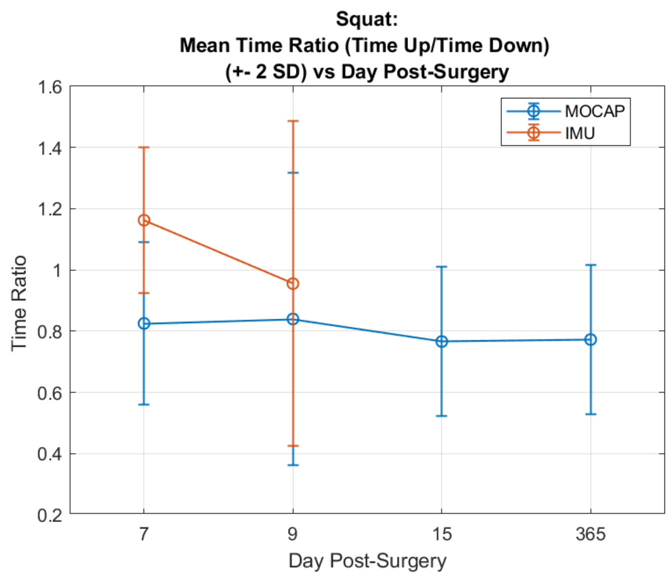

Figure B.3: Mean extension to flexion time ratio during double leg goblet squat (±2SD).

Appendix C

Additional Metrics for Single Leg Romanian Deadlift

The following recovery metrics for single leg Romanian deadlift were presented in the appendices for brevity and/or due to lack of demonstrating recovery. Metric t-test results are located in Table 3.11. Error between IMU metrics and motion capture metrics are located in Table 4.9 and effect size in Table 4.10.

C.1 Repetition Time

Figure C.1: RDL repetition time in for each day of recovery. Repetition time decreased for both the left and right leg down exercises. The difference between the affected and unaffected limbs performing the exercise decreased from $2.05s$ on day 3 to $0.977s$ on day 15.

C.2 Time Ratio

Figure C.2: RDL time ratio between the time from the bottom of the motion when the torso is parallel to the ground and the time from initial position to the bottom of the movement. Error bars are two standard deviations from the mean. The time ratio on the affected and unaffected sides became more similar as recovery progressed. Time ratio also decreased on both limbs until between day 9 and 15, when the time ratio increased on both limbs.

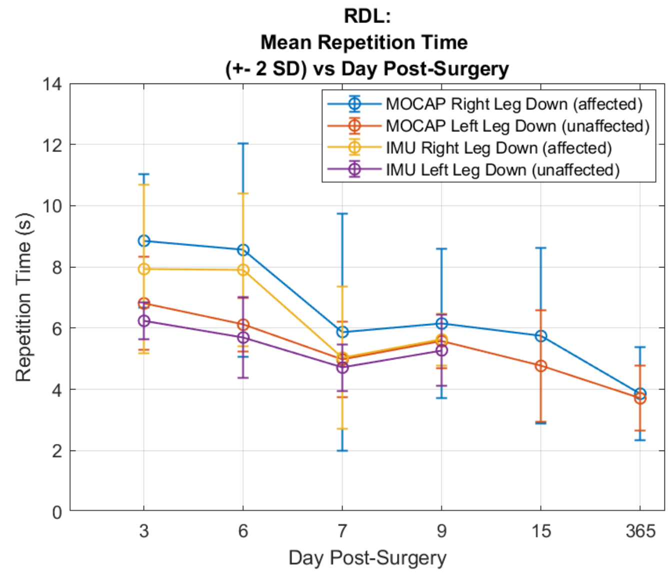

Figure C.1: Mean repetition time for the single leg RDL.

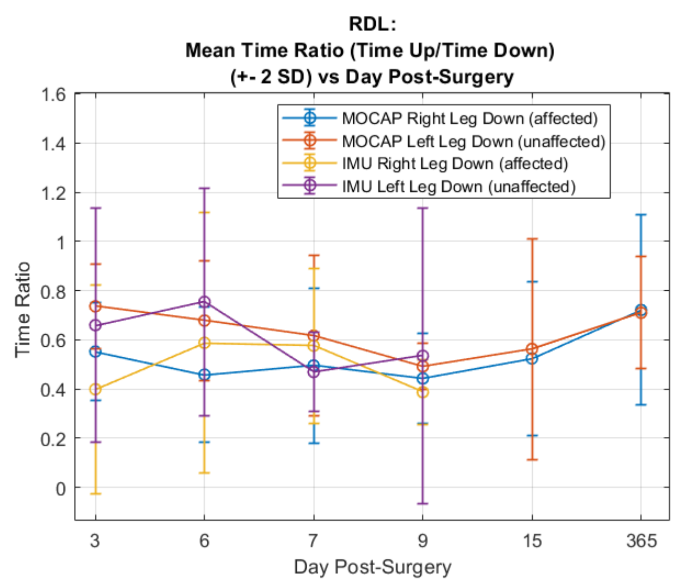

Figure C.2: Mean time ratio of flexion time to extension time during the single leg RDL.

C.3 Moving Ankle Range of Motion

Figure C.3: Ankle range of motion on the moving limb every day post-surgery, error bars are two standard deviations from the mean.

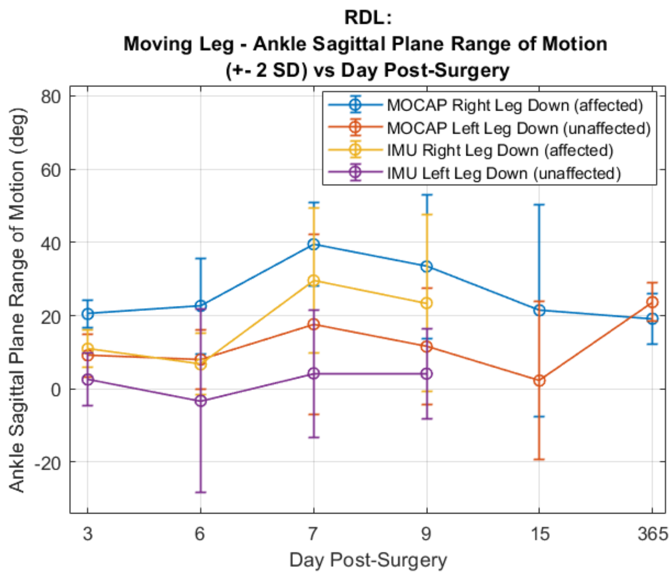

Figure C.3: Mean sagittal plane ankle range of motion for the moving leg during single leg RDL ($\pm$2SD).

C.4 Stationary Ankle Range of Motion

Figure C.4: Ankle range of motion on the stationary limb every day post-surgery, error bars are two standard deviations on either side of the mean.

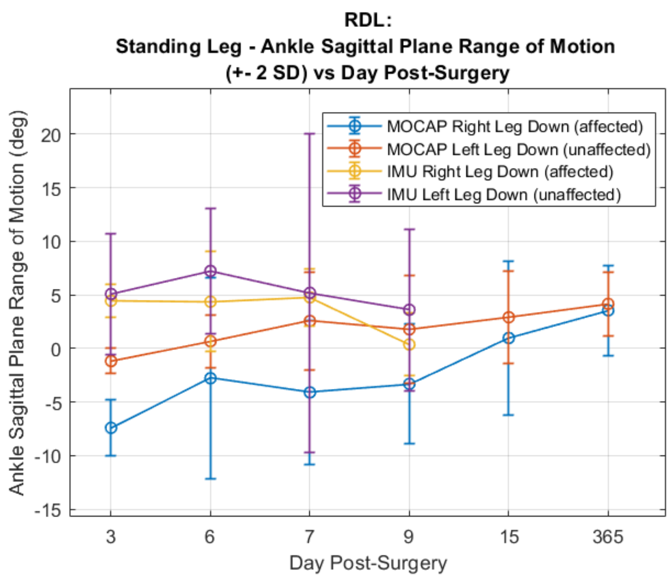

Figure C.4: Mean sagittal plane ankle range of motion for the standing leg during single leg RDL (±2SD).

Appendix D

Additional Metrics for Overground Walking

The following recovery metrics for overground straight line walking were presented in the appendices for brevity and/or due to lack of demonstrating recovery. Metric t-test results are located in Table 3.7. Error between IMU metrics and motion capture metrics are located in Table 4.5 and effect size compared to error in Table 4.6.

D.1 Sagittal Plane Ankle ROM

Ankle flexion-extension, shown in Figure D.1, was the final lower limb joint to be examined during gait. Ankle ROM was almost identical between affected and unaffected legs on all days of recovery and remained similar over recovery. Ankle flexion-extension ROM was 28.3° on day 2, 28.0° on day 3, and 26.0° on day 6 for the unaffected leg and 26.2° on day 2, 27.1° on day 3, and 25.8° on day 6 for the affected leg, which are within normative ranges (25° [85]). Both the knee and ankle for the left and right legs one year post-operation are significantly lower than the knee and ankle ROM during the recovery period, and lower than reported normative ranges.]Range of ankle sagittal plane movement showed a significant difference between day 6 and day 365 on the affected leg, again this could be due to multiple factors or demonstrate intra-subject variability.

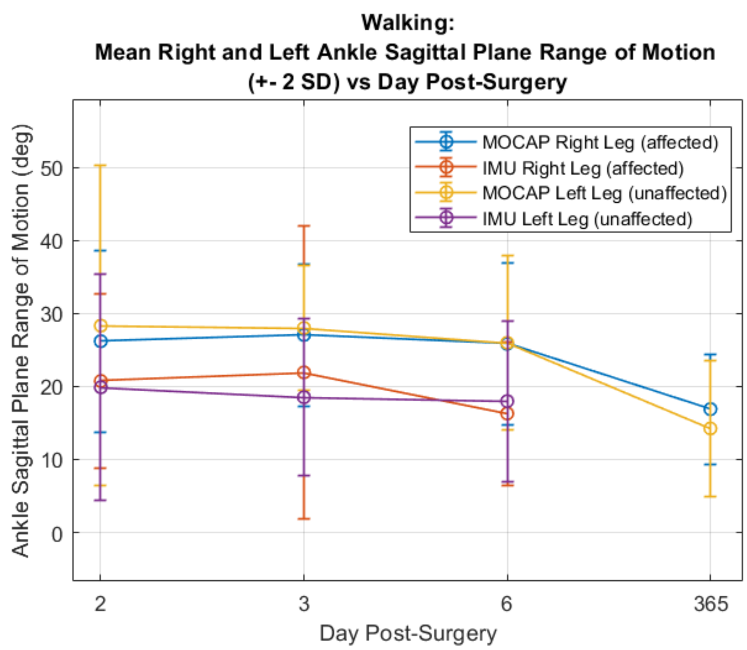

Figure D.1: Ankle sagittal plane range of motion averages for overground walking for motion capture and sensor modalities (±2SD).

D.2 Frontal Plane Hip ROM

Figure D.2 shows mean frontal plane hip ROM for both legs during swing phase. Both affected and unaffected legs had similar frontal plane ROM, corresponding to abduction-adduction motions. The affected leg frontal plane ROM was 0.410° larger on day 2, 2.52° larger on day 3, and 2.78° larger on day 6. Hip abduction-adduction are similar to normative hip abduction-adduction ROM characterized by 5-7° abduction in early swing followed by slight adduction [83].

Hip frontal plane ROM showed a significant difference on the affected leg between day 2 and 6. The left leg showed a similar trend in increasing hip abduction-adduction over the recovery period with similar values one-year post-surgery. This could indicate a recovery of frontal plane motion characteristic to the subjects walking, although values fell within normative ranges.

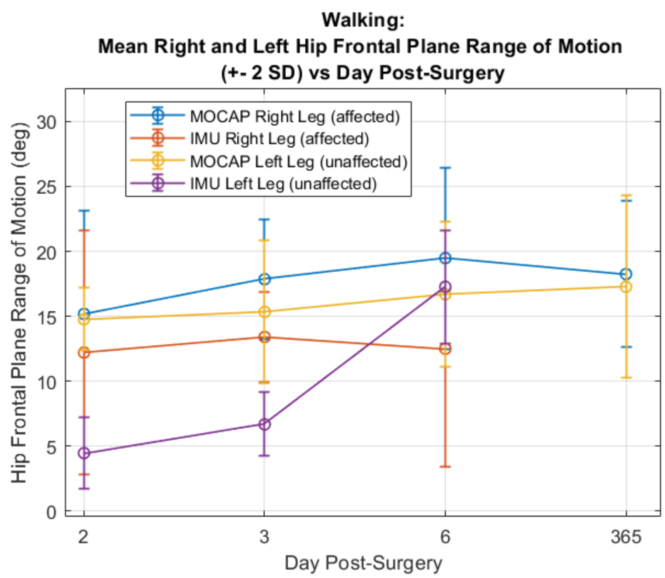

Figure D.2: Hip frontal plane range of motion averages for overground walking for motion capture and sensor modalities (±2SD).