FIGUR8

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Longitudinal Tracking of Lower Extremity Measurements During Rehabilitation Using the FIGUR8 Sensor Network

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Introduction

Determining when a patient is ready to return to active participation in sport or to a physically demanding job after an injury is a challenge for clinicians. Recovering from a musculoskeletal injury and surgical treatment can be a long and complex process with multiple factors that are specific to the individual and to the patient's job and or sport. This is particularly true for persons after an anterior cruciate ligament (ACL) tear and subsequent surgical reconstruction.

Neuromuscular control or the ability of an individual to maintain synchronized control of different segments of their body during dynamic tasks is one of the key readiness factors for return to high level activity and re-injury prevention. Poor neuromuscular control is associated with causation of initial injury and is one of the few modifiable risk factors for injuries such as tears of the ACL in the knee joint. It is difficult to objectively measure neuromuscular control as it includes multiple joints and muscle moving at the same time. Therefore, the assessment needs to be done during dynamic tasks and include monitoring multiple body parts simultaneously. Currently, clinicians rely mostly on their eyes with some using video in hopes to observe the movement pattern. This approach captures one plane of joint motion at a time as a view from the side shows how joints move in the sagittal plane while a view from the front of the person allows observation of the frontal plane of the joints. To capture information about the muscles' input to control, a sensor needs to be placed on the muscle.

The FIGUR8 sensor network has been used to provide quantitative baseline neuromuscular control screening for athletes across sports such as soccer, basketball, baseball and softball. In the following example, the FIGUR8 sensor network tracked the progress of the lower body movement patterns/neuromuscular control progress of a 23 year old female after a left patellar tendon tear repair followed by a left ACL reconstruction surgery using a right patella tendon autograph harvest. We longitudinally monitored changes in lower extremity measurements from the FIGUR8 sensor network as she underwent her physical therapy over a 7-month period. Her primary goal was to return to recreational running ~3-5 miles.

Purpose

This study evaluated the feasibility of using the FIGUR8 sensor network for longitudinal assessments for recovery tracking in a female undergoing post-surgical physical therapy after dual surgical repair including a left patella tendon repair followed 4 months later by a left ACL reconstructive surgery. The primary metrics captured during dynamic functional and rehabilitation activities included quadriceps, hamstring muscle output and hip, knee and ankle joint range of motion (ie: the bilateral deep squat and broad jump).

Aims

1. To assess the feasibility of using the FIGUR8 sensor network for monitoring longitudinal changes in quadriceps muscle output in a patient participating in the final phase of a physical therapy rehabilitation regimen.

2. To evaluate the feasibility of using the FIGUR8 sensor network for tracking improvements in dynamic joint range of motion in a patient recovering from a patellar tendon repair and an ACL reconstruction.

Methods

Participant

A 23 year old female (height -1.65 m, weight - 55.79 kg) who was 11-months post-op from an allograft repair of a 40% transverse tear of the left patella tendon and 7-months post-operative from a left knee anterior cruciate ligament (ACL) reconstruction with a right leg patella tendon autograft harvest participated in this study. She was assessed monthly over a 7-month follow-up period.

Equipment Set-up

At each study visit, to facilitate calculation of lower extremity joint angles and muscle contraction output, FIGUR8 Fusion sensors were used and the sMMG sensors were applied bilaterally across the patient's quadriceps and hamstrings. Motion Tracker devices [Inertial Measurement Unit (IMU)] were applied to the patient's pelvis and feet. The same 2 testers applied the sensors at each study visit. The FIGUR8 sensors recorded data using iOS app at 50hz streamed via Bluetooth Low Energy to a mobile device.

Data collection activities

Bilateral Deep Squat

The participant performed one practice trial and 3 data collection trials of a bilateral deep squat at six testing sessions (Figure 1). She began standing with feet shoulder-width apart and her arms extended at shoulder height. Instructions provided were to descend into a maximal bilateral squat (stopping before the hamstrings made physical contact with the gastrocnemii) and then return to the starting position at a self-selected pace. Three trials of the bilateral deep squat activity were performed. Data from the second and third trial performed during each testing session were used for analyses.

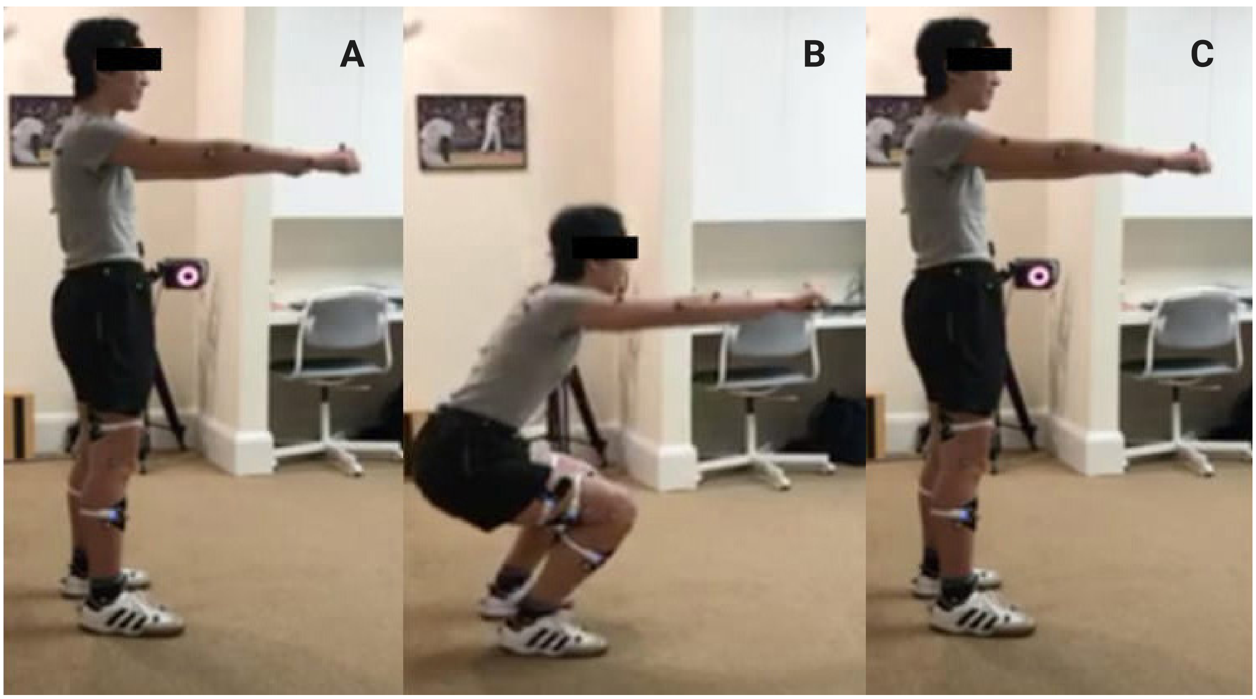


Figure 1. *Sagittal views of start (A) mid-point (B) and return to start (A) positions of the bilateral deep squat activity.*

Bilateral Broad Jump

The participant performed one practice trial and 3 data collection trials of a bilateral broad jump at seven testing sessions (Figure 2). She started in standing with her arms resting by her side and feet shoulder-width apart with the toes aligned at the edge of a measuring tape extended forward on the floor. The participant was instructed to execute a maximal forward standing long jump. Specifically, she was asked to jump forward as far as possible while taking-off from the ground on both legs simultaneously and then to "stick" the landing so that both legs made ground contact simultaneously without taking additional balance corrections such as extra steps or a small hop. The forward jump distance was measured from the start of the measuring tape to the back of her heel that was positioned closest to the starting point at landing. The participant performed 3 trials of the bilateral broad jump activity. Data from the trial with the furthest recorded jump distance performed during each testing session were used for analyses. Trials where she did not land solidly were excluded from analysis.

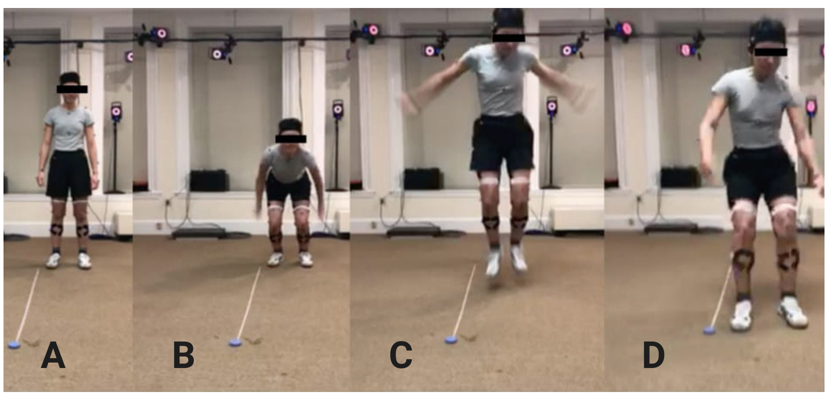


Figure 2. *Frontal views of start (A) take-off (B) in-flight (C) and landing (D) phases of the bilateral broad jump activity. The take-off phase was defined as the time from the start of the trial until the toes left the ground. The landing phase was defined as the time point from the time the toes made contact with the ground until the end of the trial.*

Data Analyses

The peak sagittal plane joint angles (°) for the hip and knee of the participant and peak physical muscle bulk displacement (mmd) during the performance of bilateral deep squat task and broad jump was recorded using the FIGUR8 sensors. The forward broad jump distance was assessed using a standard measuring tape. The second and third bilateral deep squat trial and the broad jump trial with the farthest jump distance with a "stuck" landing for each testing session were included in analyses. Statistical analyses included paired two-tailed T-Test to evaluate differences between the muscle output and joint angles exhibited by the right and left legs during an activity. The level for statistical significance was established at $p<0.05$. Sagittal plane knee and hip angle values were collected during visit 3 and visit 4 for the hip and knee respectively.

Results

Bilateral Deep Squat

The average relative contribution of the right and left legs to the total quadriceps muscle output across all visits was 51.49 ± 6.23 % and 48.51 ± 4.6.23 % respectively during the bilateral squat activity. There was an increase in the quadriceps output of both legs from the initial study visit and an alteration in the difference in output between the two legs across the study visits (Figure 3). The right quadriceps peak output increased by 23.33 mm between the 1st and 3rd visit compared to a 8.49 mm increase for the left leg between these visits, resulting in a significantly greater quadriceps output for the right leg compared to the left ($p=0.032$) at the 3rd visit (Figure 3). However, across the fifth through seventh study visits quadriceps output of right leg and left legs steadily reached similar contribution by the last study visit.

A similar trend was exhibited for the ratio of quadriceps to hamstrings muscle output for each leg during the bilateral squat across the study visits (Figure 4). The right leg ratio increased 137% from the first visit (32.04), peaking at 75.94% for the 4th visit before decreasing steadily at the remaining study visits. The left leg ratio increased less dramatically by 47% from the initial to the 4th study visit at 63.95% and then leveled off. The current FIGUR8 data base demonstrates an average of 60% Quadriceps/HS 40% ratio among healthy persons.

No significant difference in right (126.19° ± 5.74°) and left leg (124.60° ± 9.17°) peak hip flexion angle during the squat was noted across the visits ($p=0.787$). The mean contribution of the right hip (50.50° ± 1.19°) and left hip (49.50° ± 1.19°) to the total hip range of motion was highly symmetrical across available study visits (Figure 5). There was also no significant difference in measured peak sagittal knee angles for the right (120.55° ± 10.23°) and left (113.50° ± 10.76°) legs at available study visits ($p=0.171$).

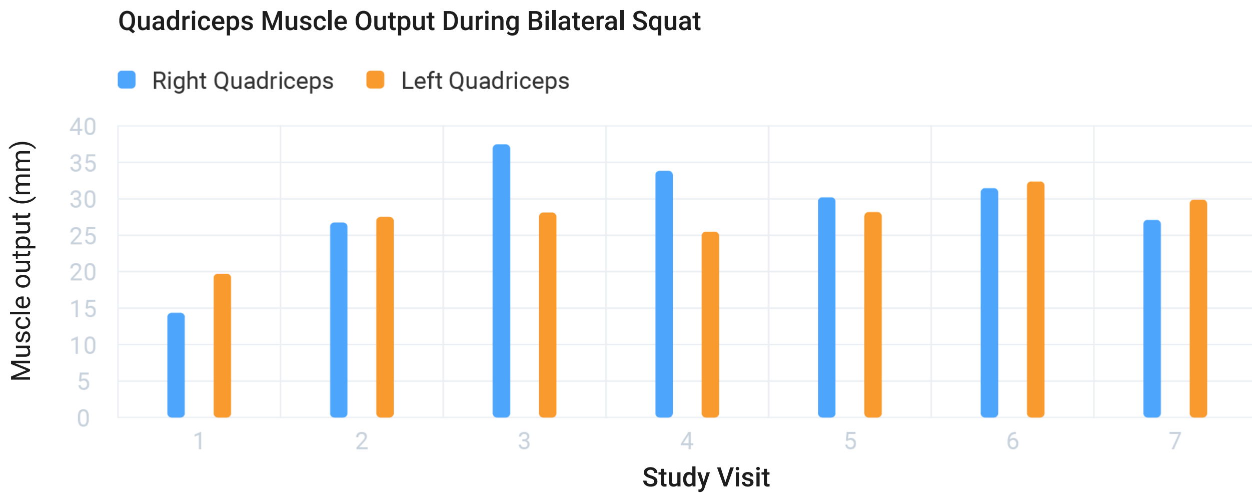


Figure 3. *Peak quadriceps muscle output during the bilateral squat across study visits.*

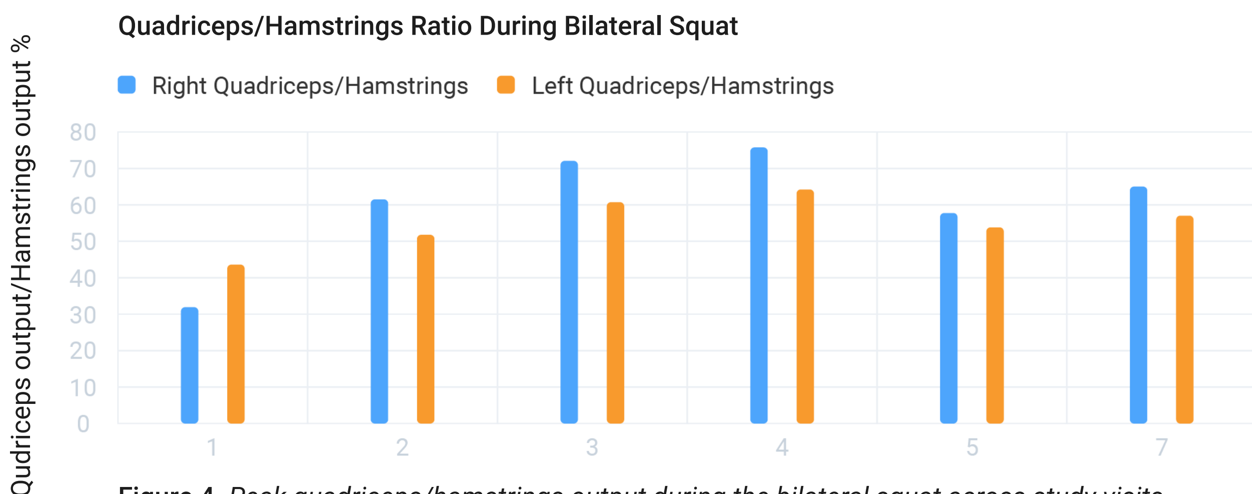


Figure 4. *Peak quadriceps/hamstrings output during the bilateral squat across study visits.*

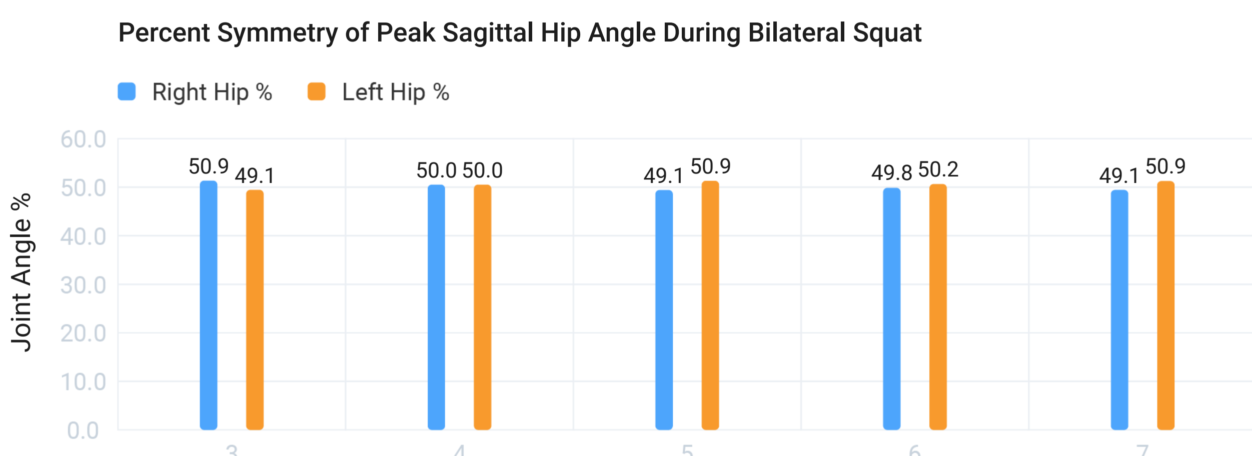


Figure 5. *Percent symmetry of peak sagittal hip angle output during the bilateral squat across available study visits.*

Broad Jump

The participant's average bilateral broad jump distance across all visits was 46.27° ± 5.61° in (range=32.00-52.25 in) with the average jump distance for each study visit presented in Figure 6 with a 12.75 in increase in best distance performance over the course of the study. The average relative contribution of the right and left quadriceps to the total quadriceps muscle output during the take-off phase of the broad jump was 45.05 ± 5.41% and 54.54 ± 5.41% respectively. Quadriceps muscle output increased for both legs throughout the study with a 9.56 mm and 9.75 mm increase for the right and left legs from the initial visit (Figure 7).

Sagittal plane joint angle calculations were added during visit 3 for the hip and visit 4 for the knee. Peak sagittal knee angles for both legs increased across available study visits for broad jump take-off (Right increase: 7.31 °, Left increase: 8.84°) and landing (Right increase: 25.67°, Left increase: 19.47°) (Figure 8). There were no significant side-to-side asymmetries in peak hip flexion angle during take-off (Right mean: 90.89 ± 4.08 °, Left mean: 91.77 ± 4.04 °, p=0.485) or landing (Right mean: 45.84 ± 8.38 °, Left mean: 42.64 ± 11.68 °, p=0.551) across available visits.

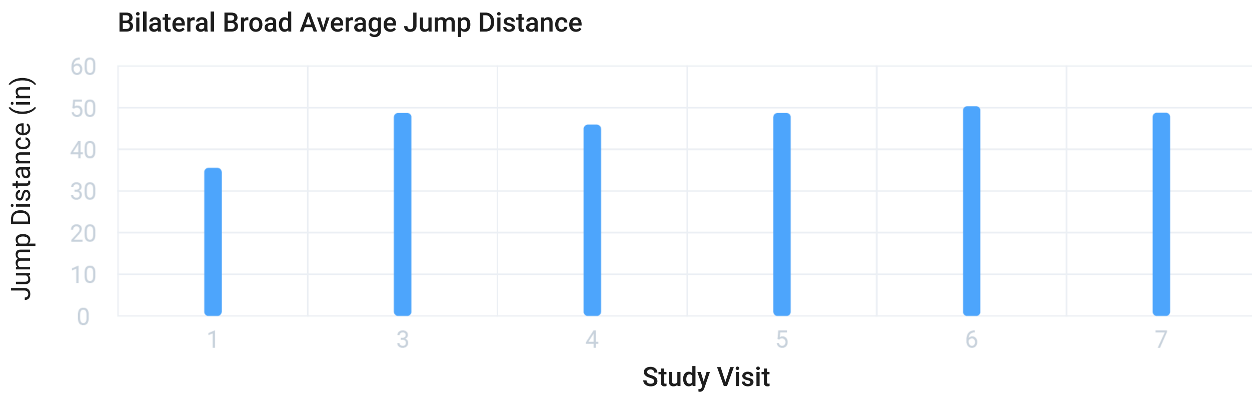


Figure 6. *Greatest broad jump distance recorded at each study visit.*

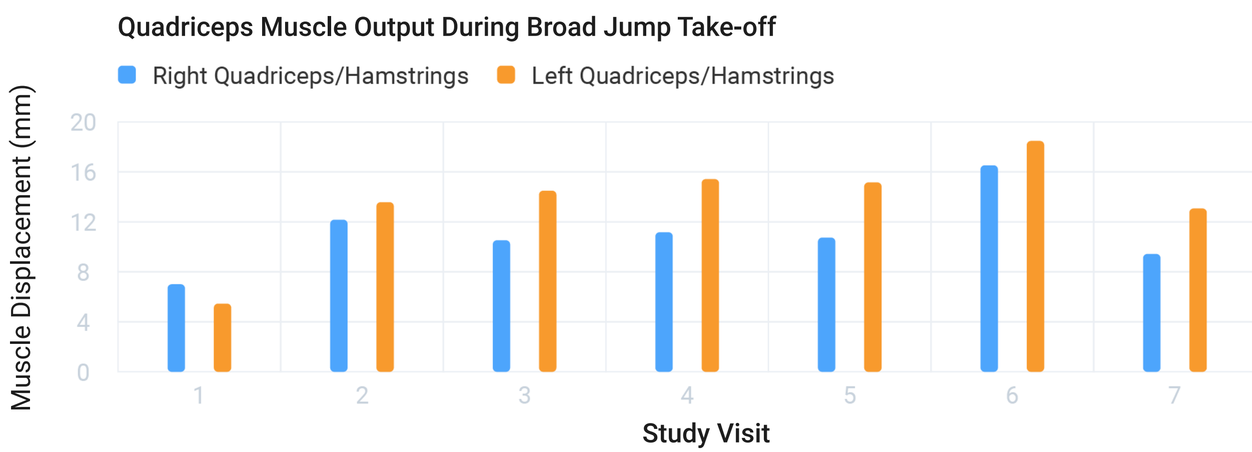
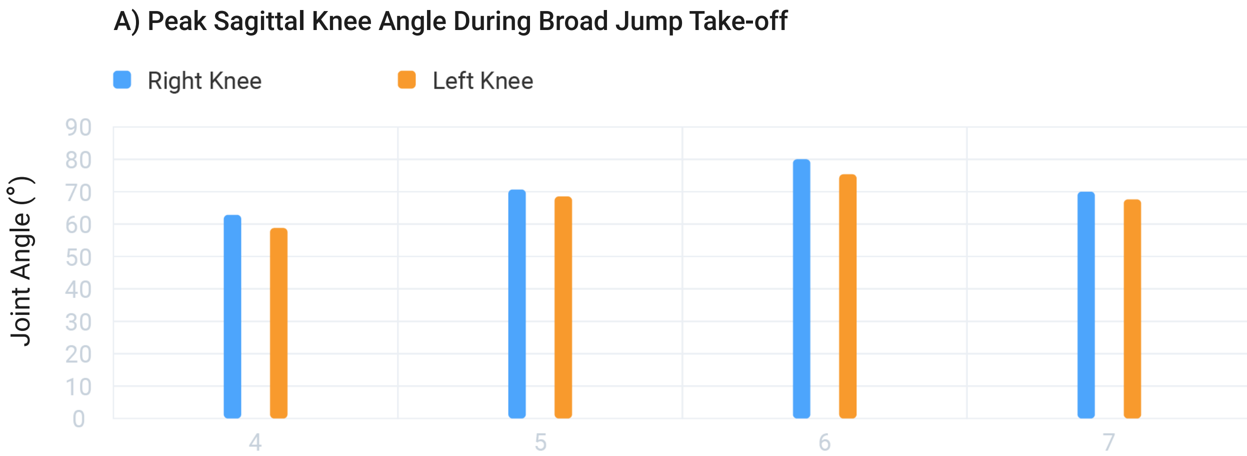


Figure 7. *Participant's peak quadriceps muscle output during the take-off phase of the broad jump across study visits.*



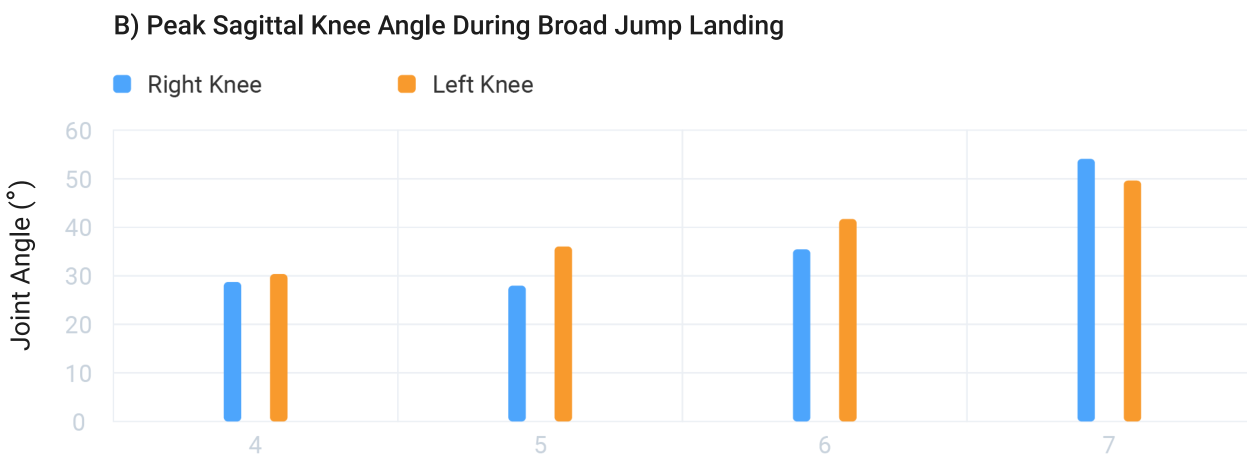


Figure 8. *Participant's peak sagittal knee angle during the (A) take-off phase and (B) landing phase of the broad jump across study visits.*

Conclusions

The study successfully demonstrated the ability of the FIGUR8 sensor network to longitudinally track changes in lower extremity muscle and joint angle measures during post knee surgery rehabilitation. Observed changes in reported metrics are also physiologically consistent with the patient's successful progression through physical therapy and clearance for more complex activities. Study observations are consistent with the expected trajectory of physical therapy where a patient often makes more rapid progress after initial clearance to perform functional activities, followed by a period of time of plateauing with similar functionality in the injured and non-injured limbs. Furthermore, recovery from major surgery is not a linear process and minor set-backs along with slow and steady generally upward trending improvements are expected. We were able to track such fluctuations during this case report.

The results from each of the neuromuscular control screening activities in this study provided additive information to provide a more complete picture on the overall progress of the patient. The findings from the bilateral squat revealed the sensor network's ability to monitor changes in lower extremity measures over time. Whereas the broad jump observations demonstrated how the FIGUR8 sensor network can track changes in performance and biomechanical technique improvements.

For the bilateral squat, there was an observed increase in quadriceps muscle output across the study visits which was consistent with the patient's completion of an ACL specific physical therapy regimen and successful return to higher level activities such as running throughout the duration of the study. Based on the emphasis of quadriceps strengthening as part of post ACL reconstruction rehabilitation protocol (in an effort to help strengthen the supporting structures around the ACL), it is expected to see an increase in quadriceps muscle bulk displacement. However, there is an established concern with ACL reconstruction patients that many of these individuals become "quadriceps dominant" partially due to the early emphasis on quadriceps activation and strengthening during physical therapy. Excessive quadriceps dominance relative to hamstrings has been shown to increase re-injury risk and re-tearing of the repaired ACL or tears to the ACL of the contralateral limb are common. Therefore, it is important to track the elevated increase in quadriceps output, especially for the right leg, that peaked around the 3rd and 4th study visits before leveling off and becoming more similar to the left leg. Furthermore, this pattern was reflected in the quadriceps/hamstrings relative output ratio. This pattern of increased quadriceps output followed by a curtailment of elevated quadriceps activation is consistent with expectations as a patient learns increased quadriceps control and an appropriate level of activation to accomplish more complex rehabilitation tasks.

FIGUR8 provides insight to muscle function through its ability to capture muscle output. The ability to identify differences between the lower extremities when there was no significant difference in the peak hip and knee flexion angle reached by both legs during the squat can direct the clinician and patient to modify exercise regime to regain muscle balance. The patient was 10-months post-op from the ACL reconstruction at the time that sagittal plane angles were collected from the FIGUR8 sensor network. It was expected that by this time point that the patient was able to squat to a similar range of motion in both legs across all study visits 4-7. Since the participant was squatting to the same depth on each leg, a visual or joint angle only assessment would suggest that the patient was relying on each leg equally during the bilateral squat activity. However, the FIGUR8 muscle data provided a greater level of complexity demonstrating that there were indeed differences in muscle involvement between the two legs with greater reliance on the non-ACL deficient leg. In other words, the patient could have been considered to successfully complete the squat activity by just watching the patient perform the task. However, the muscle data from the FIGUR8 system shows additional detail how the patient was able to improve on some functional deficits over time and by the end of the study appeared functionally similar between both the ACL deficient and non-ACL deficient legs around the time that the patient was deemed ready to graduate from physical therapy and cleared to return to all running activities. This is important since muscle asymmetries between legs have been linked to greater fatigue and a higher risk for re-injury upon return-to-sport.

Across testing sessions, an increase of 12.75 in horizontal jump distance from the initial was observed. It is also consistent with expectations that a patient relearning how to jump would see an initial improvement in jump distance before plateauing around new baseline. The results from the FIGUR8 sensor network provide quantitative measures that could help to explain this improvement in performance. For example, the sMMG sensors detected an increase in quadriceps muscle output across the study visits, with increased output positively correlating with increased jump distance. Results for greater quadriceps muscle output for the left leg compared to the right are also consistent with patient's self-report the left leg initially felt stronger when learning to jump. Additionally, the increase in functional knee range of motion demonstrated by greater peak knee flexion angles at take-off at later testing sessions could assist with power generation and greater muscle engagement. The observation of greater knee flexion angles both at take-off and landing also represent the FIGUR8 platform's ability to detect an improvement in jumping technique. Increased knee flexion can lead to more efficient push-off from the ground and is considered protective at landing to help assist with greater force absorption at ground impact. Knee flexion is also especially important to help prevent against future ACL re-injury as landing with limited hip and knee flexion has been directly linked to an increased risk for non-contact ACL injury.

This study demonstrates that the FIGUR8 platform can monitor longitudinal changes in lower extremity joint angles and muscle output in a patient recovering from lower extremity injury and returning to higher level activities. The FIGUR8 sensors detected increased symmetry, muscle output balance, and improved biomechanical movement patterns which are all indicative of improved neuromuscular control across multiple common rehabilitation return-to-sport assessment criteria activities. Sensor data on a variety of activities was able to provide unique information about the patient's progress during the activities such as the basic squat as well as the more demanding assessment tasks such as a broad jump. The ability of the FIGUR8 platform to detect these changes from a complex case is especially of note since both of the patient's legs had undergone surgery and therefore there wasn't a completely "normal" leg for the limb undergoing major reconstruction surgery to be compared against. This lack of ability to assume a healthy limb for comparison is a challenge that many physical therapists encounter while making decisions with patients on when to clear a patient to return to sport or physically demanding employment. The FIGUR8 platform provides clinically useful and actionable data to help inform return-to-sport and activity readiness.

FIGUR8