SYMMETRY OF HIP, KNEE AND ANKLE JOINT POWER DURING CYCLING WITH AND WITHOUT PAIN FROM KNEE OSTEOARTHRITIS

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.

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Abstract

Knee osteoarthritis (OA) is one of the most common chronic conditions in Canada (Bombardier et al., 2011). Commonly, the pain caused by knee OA is unequal between knees, which can lead to asymmetry of movement and joint power in daily activities. With hip and knee extensors generating the greatest proportion of power during cycling, it is unclear how the body will compensate if there is a painful knee (Elmer et al., 2011).

The purpose of this study was to investigate if seat height, workload and, any difference in knee pain, affected asymmetry of power between hips, knees and ankles during cycling. Asymmetry was defined as the difference between the dominant versus non-dominant leg. It was hypothesized that bilateral joint power would become more symmetrical as seat height increased, workload decreased and any difference in knee pain decreased.

Twenty-six participants aged 45-75 years, with and without knee OA completed six cycling bouts at three seat heights (20°, 30°, 40° minimum knee flexion angle) and two workloads (40W and 75W) on a commercial fit-bike (Pro 1, Purely Custom, USA). Self-reported knee pain on the Numeric Pain Rating Scale (NPRS) was recorded for each knee before the first bout and after each bout. Three-dimensional kinematics were collected with a commercial motion capture system (Optotrak Certus, NDI, Canada) and synchronized three-dimensional kinetics were collected with commercial instrumented 3-axis pedals (Science to Practice, Slovenia). Joint angles and power were calculated in Visual3D (HAS-Motion, Germantown, USA) for the full bout. From that full bout, a one-minute portion was selected. Then revolutions in that one-minute were averaged to one pedal cycle using custom Python code.

Seat height and workload did not have a significant effect on symmetry of joint power. A significant relationship was found between hip, knee and ankle joint power difference and knee pain

difference. The leg with the more painful knee produced less power than the opposite leg ($p < 0.001$, both workloads). Evaluating asymmetry for each joint revealed an interesting pattern. The more painful knee produced more joint power than the less painful knee ($p = 0.003$, 75W workload). The hip and ankle in the leg with the more painful knee produced less power than the contralateral joints ($p < 0.001$, both workloads). These results demonstrated the relationship between lower limb joint power and knee pain during cycling and in turn, how these joints could contribute power in the presence of knee pain. These findings are also relevant to rehabilitation clinicians, because they show rehabilitation could aim to boost the power produced by healthy joints to offload a symptomatic joint.

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List of Abbreviations

6MWT	Six-Minute Walk Test
ACR	American College of Rheumatology
ANCOVA	Analysis of Covariance
ASIS	Anterior Superior Iliac Spine
BMI	Body Mass Index
CCCARE	Center for Community, Clinical and Applied Research Excellence
cm	Centimeters
EMG	Electromyography
ES	Effect Size
ESCEO	European Society for Clinical and Economic Aspects of Osteoporosis, Osteoarthritis and Musculoskeletal Diseases
ICC	Intraclass Correlation Coefficient
iRED	Infrared Light Emitting Diodes
kg	Kilograms
KL	Kellgren Lawrence
KOOS	Knee Injury and Osteoarthritis Outcome Scale
M	Moment
m	Meters
mm	Millimeters
MVIC	Maximum Voluntary Isometric Contraction
N	Newtons
Nm	Newton-meters
NPRS	Numeric Pain Rating Scale
OA	Osteoarthritis
OARSI	Osteoarthritis Research Society International
PRF	Pedal Reaction Force
RMS	Root Mean Square
ROM	Range of Motion
RPM	Rotations Per Minute
s	Seconds
W	Watts
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index
y	Years
ω	Angular Velocity

1 Introduction

Knee osteoarthritis (OA) is one of the most common chronic conditions in Canada (Bombardier et al., 2011; Turkiewicz et al., 2014). Commonly, the pain caused by knee OA is unequal between knees, which can lead to asymmetry of movement in daily activities, such as walking and stair-climbing. This asymmetry of movement may also facilitate asymmetry of joint power (the rate of developing or transferring mechanical energy across joints (D. A. Winter, 1984)) between knees.

In healthy adults, the hip and knee extensors generate the greatest proportion of the power during cycling (Elmer et al., 2011). However, it is unclear how the body compensates if there is a painful knee. No study has specifically evaluated the compensation or share of power generation between joints or limbs, in healthy people or those with unequal knee OA pain during cycling. Additionally, there is no research into how this affects the rehabilitation of the more painful or less painful knee. In this scenario of unilateral or unequal knee OA, it is not known if cycling will improve the strength in both knees or only the less painful knee.

This study measured the joint power of bilateral hips, knees and ankles during cycling in adults with and without a pain difference between their knees due to OA. Further, this study investigated the patterns of joint power at the lower extremity joints at different seat heights and workloads. The findings expand our understanding of how lower limb joints contribute power to cycling and potential compensations for the presence of pain due to OA. Knowledge about this possible asymmetrical power aims to inform which treatment approaches should be taken to improve knee muscle strength and reduce pain in people living with knee OA.

2 Literature Review

2.1 Osteoarthritis

The most common chronic condition in Canada is arthritis and OA is the most common type (Badley et al., 2019). OA is a degenerative disorder that affects movable joints including the knees, hips and spine, and is characterized by cell stress and extracellular matrix degradation (Bombardier et al., 2011; *Standardization of Osteoarthritis Definitions*, n.d.). OA is believed to begin when damaged joint tissues cannot repair themselves, which leads to inflammation and progressive breakdown of the joint's cartilage, bone and other tissues over many years (Bombardier et al., 2011; *Standardization of Osteoarthritis Definitions*, n.d.). A diagnosis of knee or hip OA is conducted with a physical exam and assessment of the patient's history, along with radiography to assess the severity of structural damage (Katz et al., 2021). There are a range of interventions from exercise to total joint replacement to help people living with OA but there is no cure.

2.2 Prevalence Estimates

As of 2011, more than 4.6 million Canadians over the age of 20 years have OA and it is estimated that by 2040 over 10.4 million Canadians will have OA (Bombardier et al., 2011). Knee OA accounts for more than 50% of all OA cases (Turkiewicz et al., 2014). Commonly, one knee is more painful than the other. In Riddle & Stratford, 2013, a sample size of 853 had 449 individuals with unilateral knee OA (KL grade of 3 or 4, plus knee pain in one knee only).

2.3 Burden of OA

2.3.1 Pain

Pain is an unpleasant sensory and emotional experience associated with or resembling that associated with, actual or potential tissue damage as defined by the International Association for

the Study of Pain (Raja et al., 2020). Knee pain is a common symptom of knee OA that, in many cases, worsens over time and worsens with joint use (Sharma, 2021). There are multiple potential sources for this knee pain, such as the breakdown of tissues in the knee joint (e.g. synovium and subchondral bone) and the development of osteophytes (Sharma, 2021).

The level of pain experienced by a person with knee OA is related to a multitude of factors. In longitudinal studies, factors have included younger age, female sex, non-White race, lower level of educational, obesity, burden of coexisting conditions, psychological factors and pain sensitization (Sharma, 2021). While pro-inflammatory cytokines, nerve growth factors and serotonin have been determined to cause peripheral and central pain sensitization in people with knee OA (Ohashi et al., 2023).

2.3.2 Immobility

People with knee OA can experience limited mobility because of the common symptoms, including joint stiffness and pain. People with OA report having difficulty walking, climbing stairs and performing their daily self-care needs (Badley et al., 2019). Globally, 80% of patients with OA have limitations to their movement, 25% cannot perform all of their daily activities and 11% need help with personal care (March et al., 2016).

2.3.3 Quality of Life

This pain and immobility experienced by people with OA brings a negative effect on their quality of life. Compared to those without OA, people with OA have at least one more chronic condition (such as back problems and hypertension), have worse self-rated health, report more difficulty sleeping, report more pain that prevents activity and report more symptoms of depression (Badley et al., 2019; March et al., 2016). OA is also associated with an increased mortality, which is

largely due to the added presence of cardiovascular disease bought on by limited mobility and this mortality risk increases with the severity of the mobility limitation (March et al., 2016).

2.3.4 Economic and Societal

As the prevalence of OA increases, so does the economic and societal burden. There are healthcare costs paid for by the patients and government, including costs for drugs, tests and treatment, consultations with healthcare professionals, hospitalizations and services, such as home visits from support workers (Bombardier et al., 2011). The impact on the broader economy includes loss of productivity due to OA patients having reduced capacity, missing workdays and leaving the labour force entirely (Bombardier et al., 2011; March et al., 2016). These economic costs may partially account for why people with arthritis live in lower income households compared to those without arthritis (Badley et al., 2019). Working fewer hours, or not working at all, would lead to less income.

3 Rehabilitation

3.1 Pain

Many exercise and non-exercise interventions can effectively reduce knee OA pain. Both the European Society for Clinical and Economic Aspects of Osteoporosis, Osteoarthritis and Musculoskeletal Diseases (ESCEO) and the Osteoarthritis Research Society International (OARSI) recommend education, structured exercise and weight loss as core treatments for OA (Arden et al., 2021). Specifically, strength programs (e.g. isometric, isokinetic or resistance-band exercise), cycling, Tai Chi, aerobic exercise (e.g. treadmill, dance or walking) and hydrotherapy reduce pain in knee OA (Escalante et al., 2010, 2011; Messier et al., 2021). Pharmacologic interventions are also recommended by both ESCEO and OARSI, but are not core treatment recommendations (Arden et al., 2021). Pharmacologic interventions, such as oral and intra-articular medications and placebos, decrease knee OA pain (Bannuru et al., 2015). Other interventions in addition to exercise and pharmacological may contribute to symptom management, but the current evidence supporting its use remains undetermined or inconsistent. One example, kinesio taping, though not recommended by either ESCEO or OARSI, has been shown to reduce knee pain in older adults by 17.3% (self-reported pre vs post taping on 100-mm visual analog scale) in gait when applied in tension to their quadriceps (Cho et al., 2015).

3.2 Range of motion

Range of motion (ROM) is how far a person can move a joint in any given direction (Sears, 2023). Limited ROM is a common symptom of knee OA and it is associated with higher BMI, osteophytes, pain during knee flexion, bony enlargement and crepitus during knee flexion (Holla et al., 2011). ROM can be increased through exercise and non-exercise interventions. In a randomized control trial, a home stretching program had participants stretch their quadriceps femoris muscles

(while sitting on the floor) and rectus femoris muscles (while in a prone position) while holding their knees in as much flexion as possible. This program significantly improved ROM in the supine position (0.4 ± 8.6% control group (CG) vs 9.5 ± 16.2% stretching group (SG)), significantly improved gait speed (1.6 ± 11.4% CG vs 11.6 ± 10.7% SG), significantly improved ROM in gait (0.6 ± 15.2% CG vs 14.2 ± 14.6% SG) and significantly decreased pain (median values 6.5% CG vs -15.6% SG) (Aoki et al., 2009). Among 50 participants with deconditioned knees (either OA or incomplete rehabilitation after surgery or injury) stretching at end-range flexion and end-range extension produced a significant improvement in extension and flexion ROM, along with a significant reduction in pain frequency and severity on the International Knee Documentation Committee subjective survey (Shelbourne et al., 2007). The application of kinesio-tape in tension to the quadriceps of older adults increases the pain-free ROM by 23.0% (pre vs post taping measured with digital inclinometer) (Cho et al., 2015).

Cycling, however, has not been determined to improve knee ROM, stiffness or function greater than the minimal clinically important difference for each outcome, likely because the cyclist's knee does not reach their end-range flexion or end-range extension (Luan et al., 2021). Cycling also cannot alter structural elements of knee OA. Lower knee flexion ROM in people with knee OA is associated with higher body mass index (BMI), medial tibiofemoral osteophytes, severe pain on knee flexion, bony enlargement and crepitus during knee flexion (Holla et al., 2011; Luan et al., 2021). To date, cycling has been determined to decrease pain, but not improve knee ROM (Holla et al., 2011; Luan et al., 2021).

3.3 Strength

Strength is the ability to exert force (Harman, 1993). Lower knee extensor strength is associated with both an increased risk of symptomatic knee pain and a decline in knee function

(Culvenor et al., 2017). A systematic review found that strength programs based on a combination of concentric and eccentric exercises reduced pain with an effect size between 0.65 and 0.95 (with 0.2 to 0.5 being small effect size, 0.5 to 0.8 being medium effect size and 0.8 or greater being large effect size (Cohen, 1988)), while strength programs based on isometric exercises reduced pain with an effect size of 0.42 (Escalante et al., 2010). In a trial of 168 participants with mild to moderate OA (diagnosed using radiography) split into three groups (strength training, stationary cycling and usual care), the stationary cycling group and the strength training group had similar outcomes (Oiestad et al., 2023). The stationary cycling group increased their quadricep muscle strength (11.4 mean difference over usual care group; measured as isokinetic peak torque in Newton-meters) after a 12-week stationary cycling program (Oiestad et al., 2023). In another trial of 377 participants with mild to moderate radiographic OA split into three groups (high-intensity strength training, low-intensity strength training and healthy living control), both high- and low-intensity strength training groups increased their knee flexor strength significantly more than the control group without a significant difference between joint space width or knee joint compressive force measured during the 18-month follow-up (Messier et al., 2021). Both the high- and low-intensity strength training groups completed the same lower body, upper body and core exercises, but the amount of sets, repetitions and weight added to the exercises was lower in the low-intensity group (Messier et al., 2021).

Strength asymmetry has been determined to cause asymmetry and variance in gait performance. In healthy elderly women, a group (n = 11) with mean knee extensor strength asymmetry of 27.4% (percent difference between legs) also showed greater asymmetry and variance in gait compared to the more symmetrical group (n = 13, mean knee extensor strength asymmetry of 11.7%) (Laroche et al., 2012). At both standard (0.83 m/s) and maximal (self-selected) speeds, time spent in single-limb support on the stronger leg was significantly longer in the asymmetrical vs symmetrical group (mean 9.33% vs 2.87% at standard speed); while at maximal

speed, weight acceptance force was significantly higher in the asymmetrical vs symmetrical group (mean 6.35% vs 2.47%) (Laroche et al., 2012).

3.4 Aerobic Capacity

Symptoms of knee OA, such as pain and stiffness, often limit a patient's ability to perform everyday activities independently, which can lead to being more sedentary and reduced aerobic capacity (Escalante et al., 2011).The American College of Sports Medicine defines aerobic capacity as the product of the capacity of the cardiorespiratory system to supply oxygen and the capacity of the skeletal muscles to utilize oxygen ("ACSM's Guidelines for Exercise Testing and Prescription," 2022). Exercise can improve aerobic capacity in those with OA. A systematic review of 20 studies and a total of 2093 participants calculated the effect size (ES) of the effectiveness of exercise to improve aerobic capacity in people with knee and hip OA. The review showed that Tai Chi (ES = 0.66; 95% CI, 0.23-1.09), aerobic programs (ES = 0.90; 95% CI, 0.70-1.10), and mixed programs (ES = 0.47; 95% CI, -0.38-0.39) can improve the aerobic capacity of adults with hip and knee OA (Escalante et al., 2011). Additionally, in a review of aerobic fitness activities prescribed for individuals with OA and rheumatoid arthritis, a cycling program of three 25 minute session per week for 10 weeks, at either 40% or 70% of heart rate reserve, improved aerobic capacity (Westby, 2001).

3.5 Quality of Life

Quality of life is a person's ability to perform daily activities related to their personal needs, ambitions or social role in and outside their home, while not being disrupted by their disease symptoms, treatment, side effects; as well as their perceived physical well-being (Cella, 1994). Patients with knee OA commonly have symptoms that include pain, stiffness and limited knee function from inflammation and effusion, which may affect their quality of life (Luan et al., 2021). A meta-analysis of 8 studies on stationary cycling exercise for knee OA showed that daily activity, joint

stiffness and quality of life were not improved by a clinically significant amount through stationary cycling (Luan et al., 2021). Though, there is also moderate evidence that exercise therapy improves health and knee related quality of life in patients with knee OA with small to medium effects (Briani et al., 2019).

4 Cycling

4.1 Training Tool

Cycling is commonly prescribed to patients diagnosed with knee or hip OA, but it has also been used as a rehabilitation aid for patients post stroke, cardiac event and lower limb fracture or sprain (Murgoci, 2022). As previously described, cycling improves the lower limb strength and aerobic capacity of patients with knee OA. Further, a 12-month national cycling program in Australia has determined that cycling reduced BMI by a significant amount (Rissel & Watkins, 2014). Also, a systematic review of 11 studies and a total of 455 patients has determined that aerobic exercise, such as stationary cycling, has a significant antidepressant effect (Morres et al., 2019). With higher BMI being a risk factor of OA and depression a common comorbidity of OA, cycling has clear benefits to OA patients (March et al., 2016).

4.2 Leisure and Commuting

In 2013/2014, an estimated 12 million Canadians over the age of 12 used a bicycle for leisure, transport or commuting during the previous year (Ramage-Morin, 2017). Regular moderate intensity activity, which can be achieved by cycling, is associated with health benefits. Activities that become part of everyday life, such as cycling to work or school are more likely to be maintained compared to activities that require attendance at a venue, such as a fitness class at a gym (Lawlor et al., 2003).

Overuse injuries are prevalent amongst recreational cyclists. From a self-reported questionnaire completed by 294 male and 224 female recreational cyclists, 85% reported at least one overuse cycling injury; and of these, 36% sought medical attention in a one year period (Wilber et al., 1995). The most common injuries reported were to the neck and knees (Wilber et al., 1995). A systematic review of 18 studies found no strong evidence of a relationship between overuse symptoms or injury and any bike, body or load parameter. However, bike-fit professionals

(individuals who work in the sports medicine field and setup bikes for competitive cyclists) believe that both training and how a bicycle is setup (e.g. seat height) can mitigate the incidence of overuse pain or discomfort reported by cyclists (Silberman et al., 2005; Visentini et al., 2022). Also, though research looked into how bicycle fit affects pain in healthy cyclists, no research has determined how bicycle fit affects knee OA pain.

4.3 Bicycle Fit

Bicycle fit refers to how the geometry of a bicycle is adjusted, such as by raising or lowering the seat height, to suit the height of the rider. The option to adjust the vertical seat height is a common, built-in feature, while other adjustments such as crank arm length and handlebar height are far less common or require additional or replacement parts.

Crank arm length is the distance from the pedal axis to the crank arm axis (see Figure 1). This varies between 170mm and 175mm, depending on the type of bike (Gatti et al., 2022). Seat height is the vertical distance from the seat to the crank arm axis. Typically, professionals that fit bicycles will aim to set seat height with the pedal in the 6-o'clock or 180° position (top of pedal parallel to ground) and the knee positioned at the desired angle measured from full extension, typically 25° to 30° (Silberman et al., 2005). The fore/aft seat position is the horizontal distance from the seat to the crank arm axis. This is set with the pedal in the 3 o'clock or 90° position (top of pedal parallel to ground) and using a plumb line to position the most anterior point of the patella over the pedal axis (Silberman et al., 2005). The vertical and horizontal distance of the handlebars relative to the crank arm axis is a subjective measurement and positioned for rider comfort or to improve aerodynamics (Silberman et al., 2005).

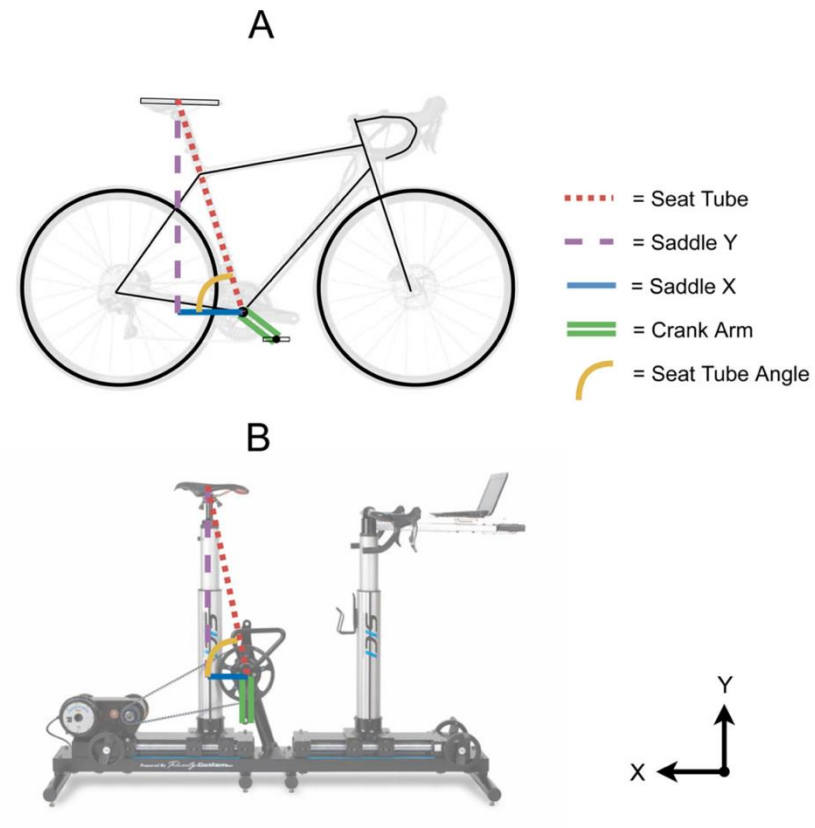


Figure 1 - Bicycle Fit Parameters – Saddle Y is the seat height and Saddle X is the seat fore/aft position (Gatti et al. 2022)

4.4 Exercise Dosage

There is no consensus on the ideal range of dosage of cycling exercise (i.e., session length, number of sessions per week, intensity of session) for the treatment of knee OA. In a review of 11 different stationary cycling exercise programs for knee OA, the session durations ranged from 20 to 60 minutes, the number of sessions per week ranged from two to five, the length of the intervention ranged from eight to 12 weeks and the intensity ranged from 40% to 80% of maximal heart rate (Luan et al., 2021). No discernible patterns emerged from the data in the meta-analysis (Luan et al., 2021).

5 Biomechanical Measures in Cycling

5.1 Force

Pedal reaction forces (PRF) refer to the reaction force (Newtons) and moment (Newton-meters) to the force of the participant pressing down on a pedal to rotate the crank arm. PRF is a required input to calculate joint forces and moments using an inverse dynamic approach. While there is no standard tool to acquire PRF, research laboratories worldwide measure PRF either using custom built tools or commercial products. In fact, most of the research to-date uses custom built tools to measure PRF, which reflects that biomechanics research in cycling is currently foundational and presents with some variability between studies.

There are advantages and disadvantages with using custom and commercial pedals in biomechanics research. Custom pedals can be designed to suit the needs of the laboratory and study, while the commercial pedals will be generic or have accessories intended to broaden applicability. A custom product could potentially be used indefinitely because the laboratory has full control and understanding of the pedals. However, custom products tend to be higher in cost, can take weeks or months to design, manufacture and test, and any replacement parts need to be fabricated. On the other hand, commercial products can be a quicker more cost-effective solution and create consistency between laboratories. However, commercial products can have long delivery times if not in stock. If the commercial pedal manufacture stops supporting their product or goes out of business, the pedals will eventually become obsolete without software or firmware updates and fixing them could be very challenging.

Custom-made instrumented pedals have been used to measure 3D pedal reaction force data by both Hummer et al., 2021 and Gardner et al., 2015. In Hummer et al. 2021, PRF was measured in the medial, posterior and vertical directions and showed decreasing seat height and increasing

workload resulted in greater peak vertical PRF. Additionally, decreasing seat height or increasing workload produces increases in internal knee extension moment in healthy, adult recreational cyclists (Hummer et al., 2021). In Gardner et al. 2015, PRF was measured in the medial, posterior and vertical directions and showed no significant group or interaction effect at neutral, 5° or 10° toe-in angles in patients with medial knee OA.

Bini et al., 2010 and Martin et al., 2007 used custom-made instrumented pedals to record normal and tangential pedal reaction forces (two-dimensional). In a validation study of an instrumented spatial linkage, Martin and colleagues (2007) determined the joint power of the ankle, knee, hip and hip transfer calculated using kinematics from their instrumented spatial linkage and their video-based motion capture system agreed within root mean square (RMS) differences ranging from 0.6 to 2 Watts. Bini and colleagues (2010) had 9 adult male participants ride a stationary bicycle at three seat heights, two cadences and three workloads and their results showed mechanical work (Joules) at the hip, knee and ankle increased as workload and seat height increased. Additionally, the proportion of the contribution from the ankle joint to total mechanical work across the lower limb increased with seat height, while the knee joint contribution decreased (Bini et al., 2010). These findings suggest there exists ankle-joint muscle tuning to control pedal force application; this tuning may compensate for lower contributions to workload from the knee and would likely minimize soft-tissue in the knee joint in healthy, male adults (Bini et al., 2010).

There is less research using commercial instrumented pedals. Buddhadev et al. 2018 used commercial instrumented pedals (Sensix, Poitiers, France) to measure 3D PRF data and then used crank position data to calculate the power of each leg, averaged over 60 crank cycles. This study showed that the leg with knee more affected by OA (higher or equivalent Kellgren Lawrence (K-L) grade, more self-reported knee pain) generated more power than the leg with knee less affected by OA (lower or equivalent K-L grade, less self-reported knee pain). This finding, which appears

counterintuitive, requires further study to understand whether this pattern is replicated in other samples and if so, the underlying mechanisms.

5.2 Kinematics

Kinematics in this study refers to the movement of the participant's lower extremity joints and limbs during cycling and is often measured in degrees (joint angle) or millimeters (three-dimensional position of joint or landmark). While not the only approach to capturing movement, camera-based motion capture is commonly used to record kinematic data during cycling. Hummer et al., 2021 used a 12-camera Vicon system (Vicon Motion Capture Inc., Oxford, UK) and showed that total knee excursion ROM in both the sagittal plane and abduction significantly increased with increasing seat height. While Gardner et al., 2015 used a 9-camera Vicon system to collect 3D kinematic data. Bini et al., 2010 used a single camera to record lower right limb sagittal kinematics.

A non-camera-based motion capture system (an instrumented spatial linkage system) was used in Martin et al., 2007, to record the position of a participant's anterior superior iliac spine (ASIS) during cycling. The linkage system was determine to have smaller error (vertical mean error: 0.03 ± 0.21 mm vs. 0.30 ± 0.55 mm; horizontal error: -0.13 ± 0.59 mm vs. -0.27 ± 0.60 mm) for 2D motion capture of the ASIS compared to a 2-camera based motion capture system (DMAS6, Spica Technology Corporation, Kihei, HI) (Martin et al., 2007). The cost of the linkage system was relatively inexpensive ($900 USD) compared to the cost of a research-grade camera-based motion capture system. The linkage system would also have comparatively less postprocessing time, but because the linkage system can only be used while a participant is stationary (e.g. while on stationary bike or treadmill), it cannot be used as broadly as a camera-based system (Martin et al., 2007).

In a healthy adult population, with seat height adjusted such that the knee fully extended when the pedal is at bottom dead center, the expected angular excursions of the hip, knee and

ankle joints in the sagittal plane are 52.8 ± 3.6°, 88.0 ± 4.4° and 39.1 ± 7.7° respectively (Li et al., 2017).

5.2.1 Cadence

Cadence describes the rate to complete full rotations of the pedals over a period of time, measured in rotations per minute (RPM). Martin et al., 2007 applied a digital encoder to the right crank to record its position. The instrumented pedals used in Buddhadev et al., 2018 had optical encoders to determine both crank and pedal orientation.

Cadence may have an impact on joint mechanical work. An increase in cadence from 40 to 70 rpm does not significantly change contribution of the hip or knee joints to total mechanical work (Joules) (Bini et al., 2010). However, this increase in cadence did significantly increase the ankle joint contribution to total mechanical work. It is important to note though, that the authors state this increase ankle contribution with faster cadence could have reflected the lower skill level of the non-cyclists in the study (Bini et al., 2010).

5.2.2 Angular Velocity

Angular velocity is the rate of change in joint angle and is measured in degrees per second. From data reflecting the position of body segments in space across multiple time points, angular velocity is calculated to reflect how fast each of the foot, shank and thigh segments are moving about the hip, knee and ankle joints on a bicycle. Studies have used Visual3D (HAS-Motion Inc.) to process motion data to generate angular velocity, along with joint angles and other 3D kinematic and kinetic measures (Gardner et al., 2015; Hummer et al., 2021). The joint angular velocity will be multiplied by the joint moment to calculate the joint power generation (D. Winter, 2009).

5.3 Power Generation

Power (Watts) is the rate of mechanical energy transfer across joints. During cycling, the muscles that cross the hip, knee and ankle joints all generate power, which is transformed to the pedals, then to the driven wheel to propel the cyclist forward. Each joint contributes to the total power generation of the limb. To be symmetrical, bilateral joints and therefore limbs should generate approximately the same amount of power. In a healthy male trained cyclist population, the hip, knee and ankle joints of the dominant leg produced an average of 14%, 37% and 49% of the joint power during one pedal cycle at a workload of 250 W and 90 rpm (Elmer et al., 2011).

5.3.1 Workload

Workload (Watts) during cycling is the power output at the pedals and equal to the power generated by bilateral hip, knee and ankle joints. Workload can be adjusted by changing the cadence or resistance to pedal rotation. For example, a Monark bicycle ergometer (GIH, Monark, Stockholm, Sweden) was used in Bini et al. 2010 to set the workload at 0, 5 and 10 N of braking force at both 40 and 70 rpm. While Buddhadev et al. 2018 used a Velotron Dynafit ergometer (Racer- Mate Inc, Seattle, WA) to control the workload to 75 and 100 W at both 60 and 90 rpm.

Individuals with knee OA have less capacity to generate power during cycling than healthy individuals. In a comparative study of exercise ambulatory capacity Sutbeyaz et al., 2007 found a significant difference ($p < 0.01$) in peak power output before exhaustion between obese adults with knee OA ($n = 28$, 45.46 W) and without knee OA ($n = 28$, 71.14 W) (Sutbeyaz et al., 2007).

5.4 Asymmetry

Asymmetry evaluates the magnitude of differences in kinematics and kinetics between the left and right limbs during performance of a symmetrical task. While bicycle fit is symmetrical, a person's kinematics and kinetics during cycling are not always symmetrical (Carpes et al., 2010; da

Silva Soares et al., 2021). Most cycling studies, however, evaluate kinematics and kinetics on only one side of the participant. This is possibly due to the cost of having enough cameras to record bilateral movement, the longer laboratory time spent setting up participants bilaterally and the increased processing demand of analyzing bilateral results.

One study found differences between knees within subjects with knee OA. Buddhadev et al. 2018, evaluated asymmetry between dominant and non-dominant legs, along with more severe OA (higher or equivalent knee K-L grade, more self-reported pain) and less severe OA (lower or equivalent knee K-L grade, less self-reported pain) within the same individual. In this study, instrumented pedals were used to measure pedal reaction force and angular velocity of each pedal, then power generation was computed and compared at each pedal. They found that the leg with more severe knee OA generated more power than the leg with less severe OA. There are several potential explanations for this unexpected finding. First, this finding suggests that the level of K-L grade is not a strong predictor of knee function. Supporting this notion, Cubukcu and colleagues (2012) showed in a cross-sectional study of 114 patients diagnosed with knee OA found no significant association between K-L grade and knee symptoms, such as pain and stiffness. Second, with only 12 participants with knee OA in the study and an effect size (Cohen's f = 0.49) calculated from their asymmetry index results, they, arguably, did not have enough participants to draw conclusion from their results. Further work is required to evaluate the impact of asymmetrical knee OA on joint power.

Asymmetrical power generation during cycling has also been found in people who have experienced cerebrovascular accidents (CVA). Perell et al., 1998, compared involved and contralateral lower limbs in participants after CVAs. The impact of a CVA on movement is variable between individuals, however a common presentation is hemiparesis, which presents as substantial asymmetry of the involved and contralateral limbs during the performance of symmetrical tasks

(Perell et al., 1998). In this study, instrumented pedals were used to measure pedal reaction force and video recorded the motion of the pedals; then power generation and generalized muscle moments were compared between hip, knee and ankle joints. Their results showed significant asymmetry in power generation between involved and contralateral lower limbs with the involved limb producing only 40% of the total positive bilateral power. The hip joint contributed the bulk of the power in the involved limb, while the most asymmetry was between ankles. The power generation patterns of the healthy control group graphically appear similar to Elmer et al., 2011, while the contralateral limb power generation patterns did not match healthy control group.

6 Knowledge Gaps

6.1 Share of Power

The contributions of each lower limb joint to total leg power and whether one limb generates more power than another in people with unequal knee OA pain between knees is not known. While Buddhadev et al., 2018 indicated that people with knee OA (where one limb was more affected by knee OA than another) demonstrated asymmetry in power generation between limbs, this study did not measure the joint power individually at each of the hip, knee and ankle joints.

This gap in knowledge has important implications. First, in someone with unequal knee OA pain between knees, it is unclear whether cycling could support rehabilitation by improving the movement and joint power of the more affected knee; or whether cycling would instead facilitate compensation by enhancing power generation by the opposite limb. Second, it remains unclear how load sharing between the hip, knee and ankle within the same limb responds to a painful knee joint while aiming to maintain task performance. Meaning, similar to the first point, it is not known if cycling could support rehabilitation by improving the joint power of the more affected knee; or whether cycling would instead facilitate compensation by enhancing power generation in the leg's hip and ankle joints.

6.2 Symmetry versus Workload and Seat Height

How a change in seat height or workload contributes to the symmetry or asymmetry of lower limb joint kinematics in not known. Previous research into adults with or without OA most often only record kinematics and kinetics on one side of the participant, therefore studies of symmetry are limited.

The implication of this gap in knowledge is that if a patient has unequal knee OA pain between knees, knowing what seat height and workload to set their bicycle at for the most symmetrical performance will support rehabilitation strategies that aim to equalize power contributions between left and right knees.

7 Purpose

7.1 Primary Objective

To compare the bilateral difference in joint power at the hip, knee and ankle joints between the dominant and non-dominant legs at different seat heights and workloads in people with and without knee pain from OA.

7.2 Secondary Objective

To determine if seat height, workload and the bilateral difference in knee pain relate with the bilateral difference in joint power between hips, knees and ankles in people with and without knee pain from OA.

7.3 Tertiary Objective

To determine if seat height, workload and the bilateral difference in knee pain relate with the bilateral difference in joint excursion between hips, knees and ankles in people with and without knee pain from OA.

7.4 Primary Hypothesis

As the height of the seat is increased and as the workload is decreased, the hip, knee and ankle power generation will become more symmetrical between limbs, across each joint, within-participants.

7.5 Secondary Hypothesis

As the height of the seat is increased, as the workload is decreased and as the bilateral knee pain difference decreases, the hip, knee and ankle joint power will become more symmetrical between limbs across each joint.

7.6 Tertiary Hypothesis

As the height of the seat is increased, as the workload is decreased and as the bilateral knee pain difference decreases the hip, knee and ankle joint excursion will become more symmetrical between limbs across each joint.

7.7 Hypotheses Justification

Peak knee extension moment decreases as seat height increases and as workload decreases, also more painful knees generate lower peak extension moment than a less painful knee (Culvenor et al., 2017; Hummer et al., 2021). Therefore, as seat height increases and workload decreases the peak extension moment between knees should become more equal, which should lead to more symmetrical joint power.

7.8 Clinical Implications

Is cycling an effective tool to rehabilitate knees in patients with unequal knee pain? For example, if the more painful knee is generating less power than the less painful knee, the more painful knee may not be generating enough power to induce muscle adaptations associated with improved physical function. Knowledge about this possible asymmetrical power generation would inform which approaches should be taken to improve knee muscle strength and reduce pain.

How does knee OA pain impact lower limb symmetry of power generation and movement while cycling? In participants with and without knee pain from OA, the results of this study will show if there exists a relationship between intensity of pain and joint power in hips, knees and ankles, along with hip, knee and ankle ROM.

How does knee and hip strength impact lower limb symmetry of power generation and movement while cycling? If there is a difference between bilateral hip and knee joint strength, the results of this study will show how this relates with power generation in the lower limb joints.

8 Methodology

8.1 Study Design

The study had a cross-sectional design with one sample that had or did not have knee pain due to knee OA. Participants visited the lab once for data collection. The visit lasted approximately 3 hours and involved a biomechanical analysis of cycling on a stationary bike-fit bicycle and quantification of maximum isometric hip and knee strength in both of legs on a commercial dynameter. Descriptive information was recorded with questionaries for self-reported knee pain, cycling experience and OA disease. The same protocol was completed by all participants whether they met or did not meet the clinical criteria indicating symptomatic knee OA.

8.2 Participants

8.2.1 Inclusion Criteria

This study recruited people aged 45-75 years with and without symptomatic knee OA. Those who had knee pain meet the American College of Rheumatology (ACR) clinical examination classification for unilateral or bilateral knee OA (Altman et al., 1986). The ACR classification criteria includes knee pain plus at least 3 of the following 6 clinical signs or symptoms: i) be 50 years or older; ii) morning stiffness for less than 30 minutes; iii) crepitus with active motion; iv) bony tenderness upon palpating margins of joint; v) bony enlargement; and vi) no signs of palpable warmth of the synovium (Altman et al., 1986).

8.2.2 Exclusion Criteria

People were excluded from this study for any of the following reasons: (i) if it was unsafe for them to exercise based on the Get Active Questionnaire; (ii) if they self-reported an injury to their lower extremities within the past 6 months and were actively participating in rehabilitation; (iii) if

either of their ankle or hip joints were compromised (for example, with OA, rheumatoid arthritis or other issue); (iv) if they had a hip, knee or ankle joint replaced; (v) if they exceeded 250 lbs, which reflects the weight limit of the bicycle; (vi) if they engaged in cycling races or cycled more than 8 hours per week within the past year (Bini & Hunter, 2023).

8.2.3 Recruitment Strategy

Participants were recruited through posters, email newsletters, word-of-mouth in Kitchener-Waterloo and the surrounding area, and from an existing list of over 200 people who consented to be contacted about participating in research studies in the Mobilize Lab. Posters were placed around the University of Waterloo campus including the Center for Community, Clinical and Applied Research Excellence (CCCARE), in local yoga studios, bicycle shops and physiotherapy clinics. Participants who were interested in learning more about the study were instructed to contact the student investigator via telephone or email for study details. After any questions had been answered and the potential participant remained interested in study participation, they were screened during a phone call with the inclusion and exclusion criteria. Those that met the criteria were invited to enroll and complete written, informed consent.

8.2.4 Sample Size Estimation

To estimate the sample size, partial eta squared values for the effect of seat height (0.52) and work rate (0.88) on internal knee extensor moment were used (Hummer et al., 2021). An alpha value of 0.05 and 80% power was assumed. Using the values stated with ss.2way in R, the estimated sample size was 18 participants. Because previous research indicated that not all participants were able or willing to complete all elements of the protocol and some participants drop out, the recruitment target was 25 participants.

8.3 Stationary Bicycling Set-up and Protocol

8.3.1 Equipment

A fully adjustable commercial fit-bike (Fit Bike Pro, Purely Custom, Twin Falls, ID, USA) was used for this study. Instrumented pedals that measured three-dimensional forces and moments (Science to Practice, Ljubljana, Slovenia) were installed onto the fit-bike. Crank arm length was set at 172.5mm, a middle size for commercial bikes (Gatti et al., 2022).



Figure 2 - Participant on fit-bike – During cycling bouts, each participant was shod in athletic shoes with their foot secured to the pedal using a Velcro strap. Participants wore shorts and a t-shirt to enable motion tracking with skin mounted rigid bodies with markers.

8.3.2 Summary of Protocol

Participants were invited to the lab for a single visit. They were asked to wear shorts, t-shirt and athletic shoes (shoes were removed for measurement of overall height and body mass). First, questionnaires were completed to record their descriptors, anthropometrics, cycling experience, initial bilateral knee pain (Numeric Pain Rating Scale (NPRS)) and Knee Injury and Osteoarthritis Outcome Scale (KOOS). Next, they were asked to compete a six-minute walk test to characterize their knee function.

Then, the participants completed six separate cycling bouts at three seat heights (20°, 30° and 40° minimum knee flexion angle) and two workloads (40kW (feels like walking at an average pace) and 75kW (feels like walking at an average pace up a gentle incline)) (Buddhadev et al., 2018; Gatti et al., 2021; Hummer et al., 2021). The cadence for all bouts was 60 rpm. The tablet on the fit-bike continuously showed the participant their cadence. Participants were asked to maintain their cadence within a range of +2/-2 rpm. The seat height and workload were selected in a pseudo-random order, where seat heights were randomized and workloads randomized within seat heights. The participant's shoes were secured to the pedals with a Velcro strap. With the participant's left foot on the pedal and the pedal in the bottom dead center position (see Figure 5) vertical seat height was set using an universal manual goniometer to measure the knee angle (Silberman et al., 2005). Then the participant's left foot and pedal was moved to the 90° position and the fore/aft position of the seat was set using a plumb line to ensure the most anterior point of the patella is over the pedal spindle (Silberman et al., 2005). Handlebar vertical height and fore/aft distance was adjusted to the participant's comfort. Three-dimensional kinematics were collected with a commercial motion capture system and synchronized three-dimensional kinetics were collected with a commercial instrumented three-axis pedals during each bout. Details of this instrumentation are provided in section 8.4.

Self-reported knee pain for each knee on the NPRS and self-reported comfort (0-10 scale with 10 being most comfortable and 0 being least) were recorded before the first bout, then after each subsequent bout. Additionally, before the first bout and after the last bout, the participants cycled a few revolutions at a self-selected slow pace on the fit-bike at 30° minimum knee flexion and at a high resistance; during these slow revolutions, participants were asked to identify whether any specific portions of this range of motion is specifically associated with pain (i.e., a painful arc); and rate their knee pain within (see Figure 4). The participants were also asked to pause for five seconds at both the start and end of these painful portions of the range of motion where their joint angles were recorded with the motion capture system. The last step of the protocol recorded the participant's bilateral MVIC for hip and knee extensors on a commercial dynamometer.

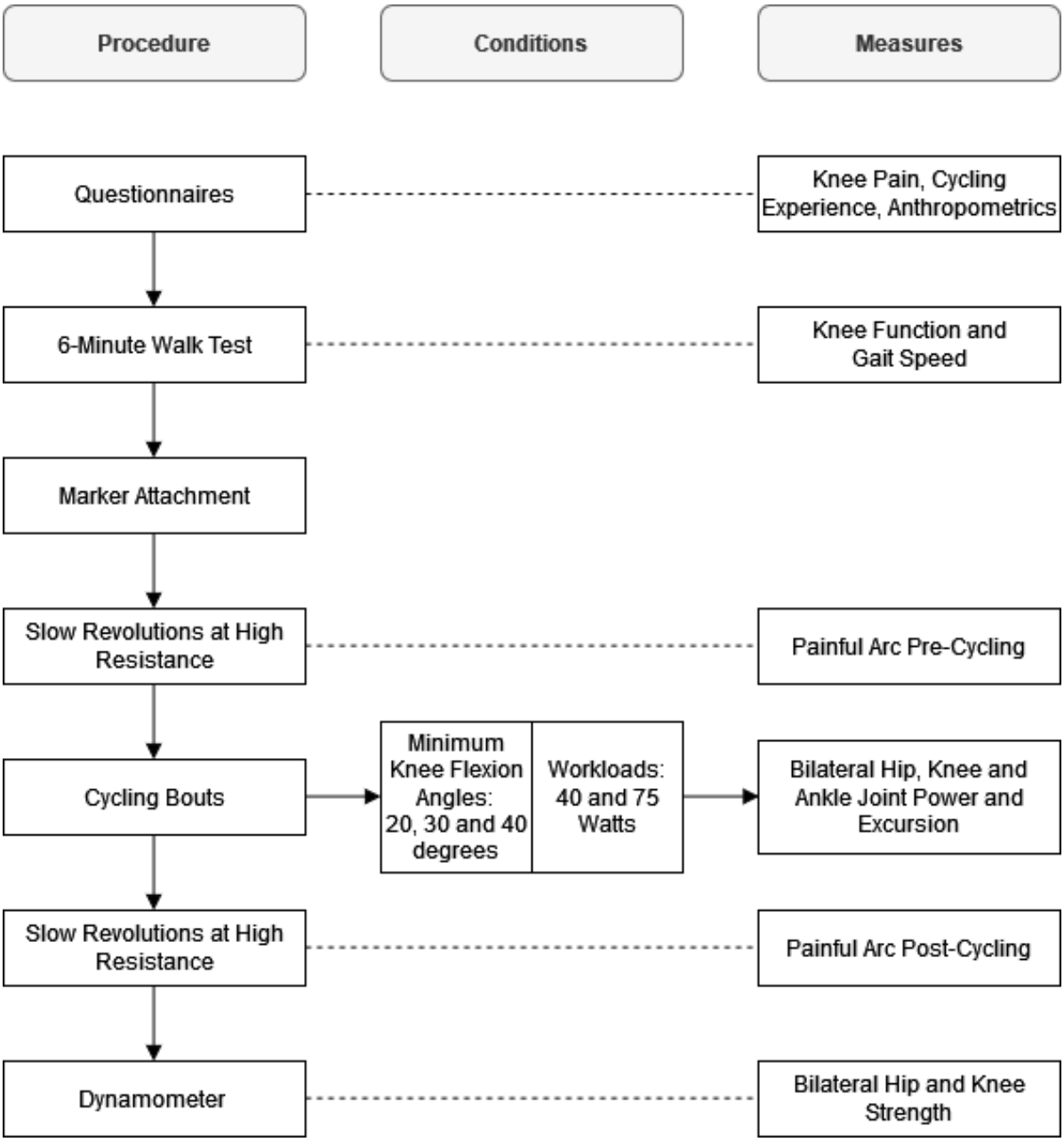


Figure 3 – Visual representation of study protocol, conditions and measures

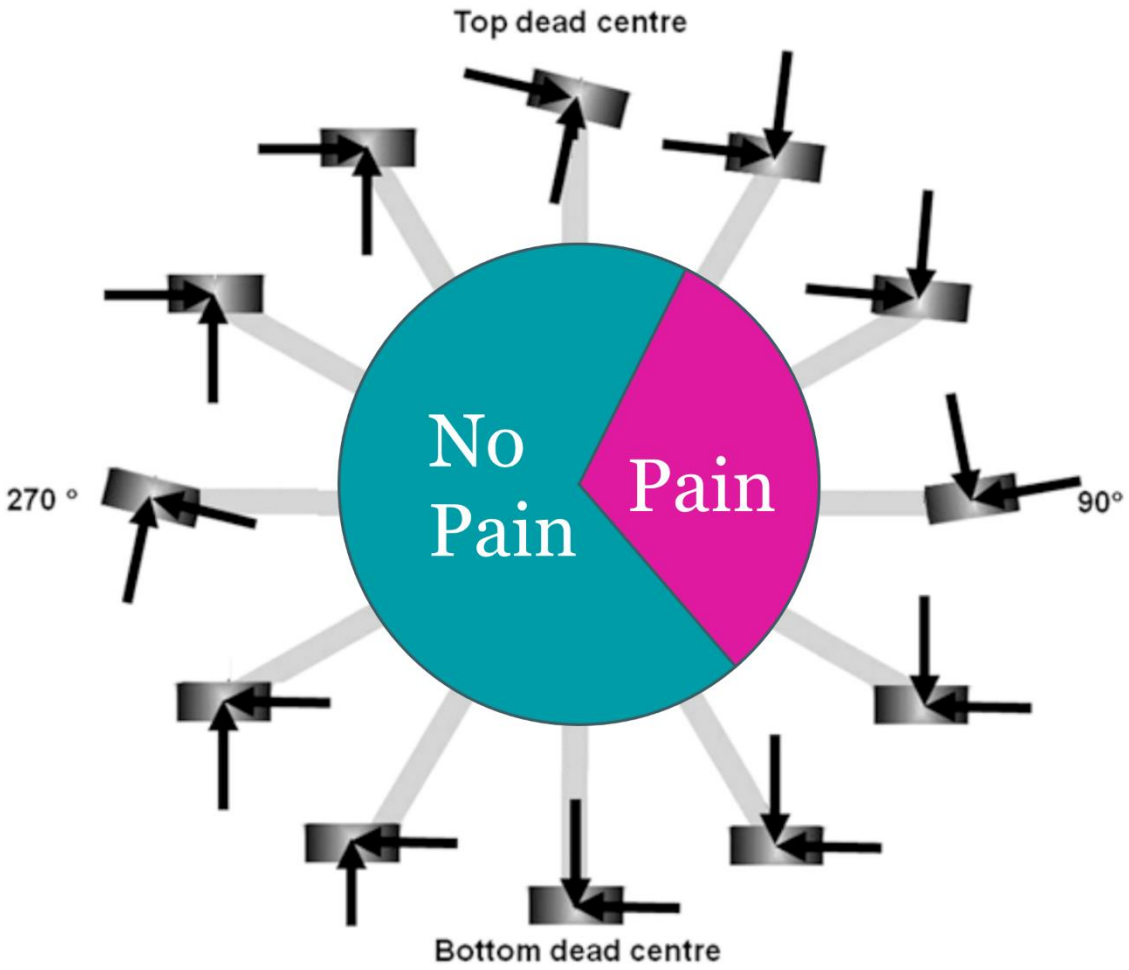


Figure 4 - Example of possible painful arc location. Modified from Bini & Carpes, 2014

8.3.3 Full Pedal Cycle

One full pedal cycle was defined as one complete 360° rotation of the pedals starting with the pedal at the 0° or 360° position. The 0° position of the pedal represented top dead center (Figure 5), while the 180° position of the pedal represented bottom dead center and the arc from 0° to 180° was the power phase, while the arc from 180° to 0° was the recovery phase (Bini & Carpes, 2014; Elmer et al., 2011).

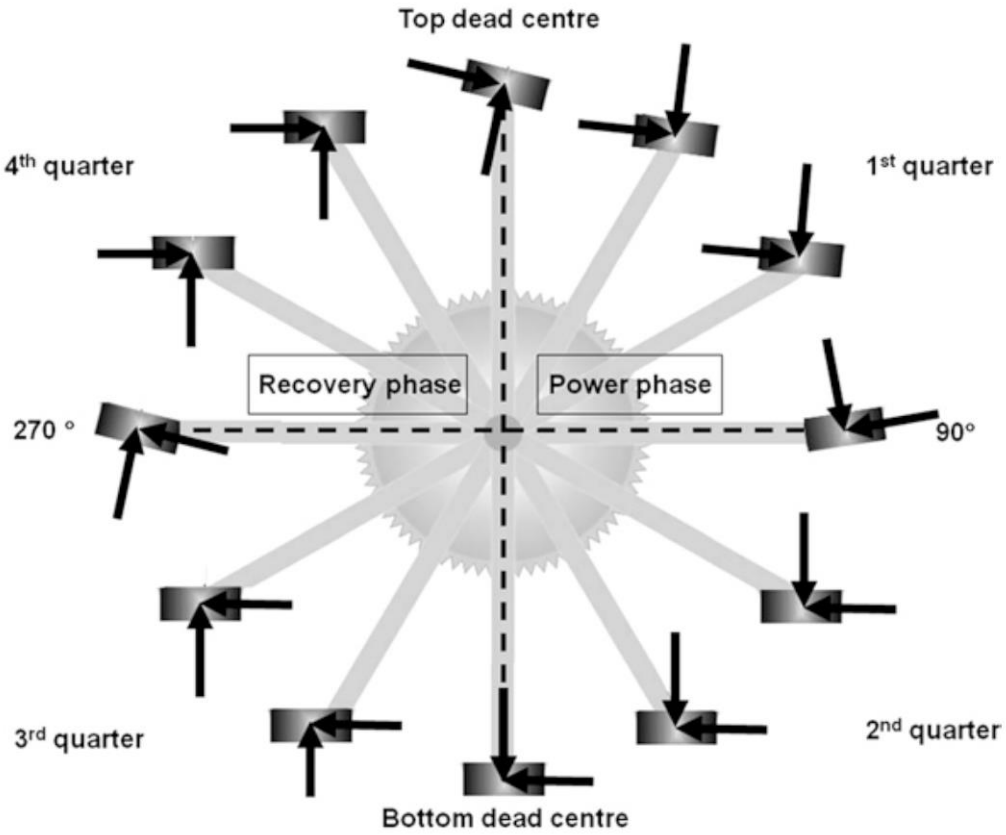


Figure 5 - Bicycle Pedalling Phases where top dead centre is 0° and bottom dead centre is 180° (Bini & Carpes, 2014)

8.4 Measures

8.4.1 Kinematics

8.4.1.1 Motion Capture System

Instrumentation, data collection and processing. A five-camera bank (15 cameras) high-speed motion capture system (Optotrak, Certus, Northern Digital Inc., Waterloo, ON, Canada) recorded three-dimensional kinematics sampled at 90 Hz to synchronize with the 450 Hz sample rate of the pedals. Participants were shod in an athletic shoe, wearing shorts and t-shirt. Rigid body clusters containing triad-oriented infrared light emitting diodes (iRED) were attached to the participant's sacrum, both thighs, both shanks and both shoes, in addition to both pedals on the fit-bike. The digitized anatomical landmarks specified in Table 1, along with functional knee joint and

hip joint trials, were used to build seven rigid, linked bodies for the pelvis and lower segments (bilateral thigh, shank and foot) (Gardner et al., 2015; Kozlovič et al., 2021; Moore et al., 2010). A sitting calibration trial was used to transform the nine-segment external markers to a reference frame. In addition, a standing trial in the anatomical position was captured as a backup. The cycling bouts were filtered at an 8Hz cut-off frequency and with a fourth-order zero lag low-pass Butterworth filter (Elmer et al., 2011).

Table 1 - Digitized anatomical landmark locations for foot, shank, thigh, pelvis and pedals with their respective rigid body cluster. Note: (L) = left; (R) = right.

Digitized Marker Number	Digitized Anatomical Landmark	Rigid Body Cluster
1	(R) Posterior Superior Iliac Spine	Sacrum
2	(L) Posterior Superior Iliac Spine	Sacrum
3	(R) Iliac Crest	Sacrum
4	(L) Iliac Spine	Sacrum
5	(R) Anterior Superior Iliac Spine	Sacrum
6	(L) Anterior Superior Iliac Spine	Sacrum
7	(R) Greater Trochanter	Right Thigh
8	(R) Lateral Epicondyle	Right Thigh
9	(R) Medial Epicondyle	Right Thigh
10	(R) Lateral Malleolus	Right Shank
11	(R) Medial Malleolus	Right Shank
12	(R) 1st Metatarsal Head Medial	Right Foot
13	(R) 5th Metatarsal Head Lateral	Right Foot
14	(L) Greater Trochanter	Left Thigh
15	(L) Lateral Epicondyle	Left Thigh
16	(L) Medial Epicondyle	Left Thigh
17	(L) Lateral Malleolus	Left Shank
18	(L) Medial Malleolus	Left Shank

19	(L) 1st Metatarsal Head Medial	Left Foot
20	(L) 5th Metatarsal Head Lateral	Left Foot
21, 22, 23	(R) Pedal Surface Corner 1A, 1B, 1C	Right Pedal
24, 25, 26	(R) Pedal Surface Corner 2A, 2B, 2C	Right Pedal
27, 28, 29	(R) Pedal Surface Corner 3A, 3B, 3C	Right Pedal
30, 31, 32	(R) Pedal Surface Corner 4A, 4B, 4C	Right Pedal
33, 34, 35	(L) Pedal Surface Corner 1A, 1B, 1C	Left Pedal
36, 37, 38	(L) Pedal Surface Corner 2A, 2B, 2C	Left Pedal
39, 40, 41	(L) Pedal Surface Corner 3A, 3B, 3C	Left Pedal
42, 43, 44	(L) Pedal Surface Corner 4A, 4B, 4C	Left Pedal

Reliability and validity. The Optotrak Certus is a precise and reliable tool for the analysis of gait (Mazumder et al., 2007). Reliability and validity of the Optotrak Certus was assumed to be acceptable for stationary cycling even though it has not been tested for this task, because the speed of movement and joint angles of gait and stationary cycling are similar. Mazumder and colleagues (2007) used a robot capable of three-dimensional moment to quantify the accuracy and precision of the Optotrak Certus. Precision between markers was found to be excellent in static conditions (% error = 0.57, SD (mm) = 0.002-0.0043), dynamic conditions (% error = 0.57-0.58, SD (mm) = 0.0058-0.0086) and angles between markers in static conditions (% error = 4.01, SD (°) = 0.00013-0.00019) (Mazumder et al., 2007). While repeatability was found to be moderate for constant speed (coefficient of multiple correlation (CMC) = 0.63, SD(mm/s) = 0.26), but excellent for angle (CMC = 0.99, SD(°) = 0.10), volume (CMC = 0.99, SD(m^3) = 0.000015) and circular movement in x-axis (CMC = 0.99, SD(m) = 0.0094) and y-axis (CMC = 0.99, SD(m) = 0.0082) (Mazumder et al., 2007, 2011).

Assumptions and Limitations. The rigid-linked model assumes the participant's involved segments are rigid, while the motion capture markers are assumed to be rigidly attached to these

segments. Assuming segment rigidity simplifies mathematical calculations and creation of a local coordinate system for the segment (Robertson et al., 2014). Assuming the motion capture markers are rigidly attached to the segment ignores the relative movement between the skin and bone for the pelvis, thigh and shank markers (soft tissue artifact) and ignores the relative movement between the shoe and bone for the foot marker. Therefore, there will be error between the recorded and actual motion of the segments, but this error was limited by the careful placement and attachment of rigid marker clusters and precision in the location of anatomical landmarks (Camomilla et al., 2017).

8.4.1.2 Joint Position, Angle and Angular Velocity

Joint position was measured in millimeters (mm), joint angle was measured in degrees (°) and joint angular velocity was measured in degrees per second (°/s). These values were calculated using commercial software (Visual3D, HAS-Motion, Kingston, ON, Canada). Following the right-hand rule, ankle plantar flexion, knee flexion and hip extension were positive. Additionally, hip adduction/varus, knee adduction/varus and ankle inversion were positive. Lastly, hip, knee and ankle internal rotation were positive.

8.4.2 Kinetics

Instrumented pedals (Forped, Cycling Science, Ljubljana, Slovenia) collected bilateral forces in Newtons (N) and moments in Newton-meters (Nm) in 3-dimensions at a sample rate of 450 Hz (Gatti et al., 2022). Kinetic data was filtered using the same method as the kinematic data.

Reliability and validity. These instrumented pedals produce data with good to excellent reliability for reliability for inversion / eversion torque (max (Nm): Cronbach's Alpha (CA = 0.958, Intraclass Correlation Coefficient (ICC) = 0.963; min (Nm): CA = 0.991, ICC = 0.985), internal / external rotation (max (Nm): CA = 0.891; ICC, max (Nm) = 0.906; min (Nm): CA = 0.700, ICC = 0.735),

tangential force (max (N): CA = 0.971, ICC = 0.975; min (N): CA = 0.987, ICC = 0.989) and normal force (max (N): CA = 0.884, ICC = 0.896; min (N): CA = 0.949, ICC = 0.868), though less reliability in max transverse force (max (N): CA = -0.370, ICC = -0.460; min (N): CA = 0.978, ICC = 0.964) (Kozlovič et al., 2021).

8.4.3 Joint Power Generation

Power generation at the hip, knee and ankle joints was calculated in the sagittal plane, relative to each participant's ankle, shank, thigh and pelvis segments by inputting data from the instrumented pedals and motion capture into a bilateral rigid-linked model of the foot, shank, thigh and pelvis, and using Equation 1.

$$P = M * \omega \qquad Equation\ 1$$

Where P is the joint power in Watts (W), M is the moment at the joint in Nm and ω is the angular velocity of the joint in °/s.

Joint power was calculated for the full bout, then sixty full pedal cycles from each bout was averaged to a single revolution. Further details of the data processing steps can be found in section 8.7 Cycling Bout Data Processing.

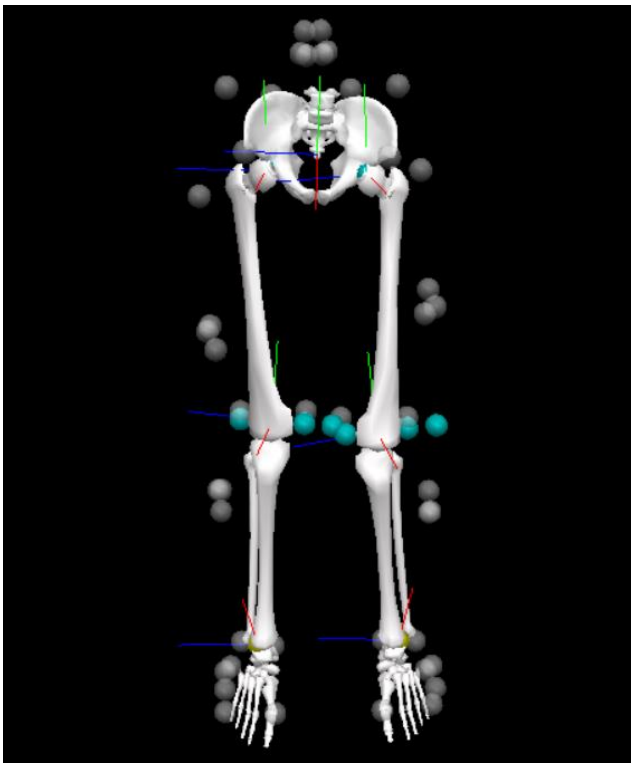


Figure 6 - Rigid-linked model from Visual3D – three markers on each foot, shank and thigh cluster and six markers on the pelvis cluster. Grey dots represent cluster markers and digitized landmarks. Teal dots represent functional joint centers and digitized landmarks adjusted by functional joint centers, which were calculated in Visual3D

8.5 Covariates for the Primary Objective

8.5.1 Hip and Knee Joint Muscle Strength

Bilateral hip and knee MVIC extensor muscle strength was measured with a commercial dynamometer and normalized to body mass. Flexor muscle strength was not measured, because the extensor muscles produce the dominant amount of power during cycling (Elmer et al., 2011).

8.5.1.1 Dynamometry

Instrumentation, data collection and processing. A commercial dynamometer (System 4 Pro, Biodex, Shirley, New York, USA) was used to measure maximum voluntary isometric contractions (MVIC) of each participant's knees and hips.



Figure 7 – Hip(left) and knee(right) maximum voluntary isometric contraction (MIVC) setup on the Biodex dynamometer

Reliability and validity. The reliability and validity of isometric knee and hip joint strength measurements with the Biodex System 3 Pro has been detailed in a number of studies and it is assumed that the Biodex System 4 Pro will have equivalent reliability and validity (Brisson et al., 2018; de Araujo Ribeiro Alvares et al., 2015; Goncalves et al., 2021). Isometric knee strength captured by this system was demonstrated to have high reliability (ICC (Nm/kg) = 0.91) (Brisson et al., 2018). The reliability of isometric hip extension strength is also demonstrated to be high (ICC (Nm) = 0.95) (Goncalves et al., 2021).

Set-up. Participants were positioned in the dynamometer for the knee (Biodex Rehabilitation - Educational, 2019b) and hip (Biodex Rehabilitation - Educational, 2019a) MVIC protocols consistent with the manufacturer's recommended procedure. For the bilateral hip protocol, participants lay on their back with trunk flexion at 0° and a strap secured their pelvis to the seat (see Figure 7). The cuff securing their thigh was located 4-5 cm above the femoral condyles and the hip joint center was aligned with the rotational axis of the dynamometer. For the bilateral knee protocol, they were positioned at 85° of trunk flexion and straps secured their pelvis, thigh and

upper torso (see Figure 7). The cuff securing their shank was located 2-3 cm above the malleoli and their knee joint center was aligned with the rotational axis of the dynamometer.

Bilateral knee and hip extensor isometric strength protocol. The MVIC protocol measured bilateral knee and hip strength in extension and consisted of five trials per joint (four joints, therefore 20 trials total; five second isometric contractions with one minute rest break between trials). The MVIC for the hip and knee extensors was measured at 60˚ of hip and knee flexion (Stearns et al., 2013). Positive verbal encouragement and visual feedback was provided to the participant during the trials to maximize voluntary effort. Peak torque magnitudes were identified from the best three trials for each joint, averaged and then normalized to body mass (Nm/kg) to represent each of a participant's maximum left and right, hip and knee isometric extensor strength.

8.5.2 Self-reported Pain

Separate Numeric Pain Rating Scale (NPRS) scores were used to record each participant's self-reported pain for each left and right knee. The NPRS is an 11-point scale (0 (no pain) to 10 (worst imaginable pain)) (Alghadir et al., 2018). Participants self-reported their pain on the NPRS for each knee before the first bout and after each bout of cycling. Additionally, before the first bout and after the last bout, the participants cycled a few revolutions on the fit-bike at 30° minimum knee flexion and at a high resistance. During those revolutions, participants were asked to identify whether any specific portions of this range of motion is specifically associated with pain (i.e., a painful arc); and rate their knee pain within. The participants were also asked to pause at both the start and end of these painful portions of the range of motion, where their joint angles were recorded with the motion capture system.

Reliability and Validity. The NPRS produces scores with excellent test-retest reliability (ICC = 0.95) and has been validated against the Visual Analog Scale (r = 0.94) for middle-aged to older adults with knee OA (Alghadir et al., 2018).

8.5.3 Excluded Covariates

A number of potential covariates were considered for this study but were not used because literature showed that these variables were not related to joint power or joint excursion during cycling.

8.5.3.1 Age

The power generation capacity of either limb depends on the strength across the hip and knee joints. Therefore, in lieu of age, hip and knee joint strength were covariates. Sarcopenia (the loss of muscle strength and mass) is a consequence of aging, but through exercise muscle strength can be maintained and increased as adults age (Caserotti et al., 2008).

8.5.3.2 Sex

Power generation between limbs had no significant difference between sexes (Buddhadev et al., 2018).

8.5.3.3 Height

Height was a descriptor along with the length of both the shank and thigh. This was measured while the participant was wearing socks, a t-shirt and shorts.

8.5.3.4 Body Mass

Body mass was a descriptor. This was measured while the participant was wearing socks, a t-shirt and shorts.

8.5.3.5 Ankle Joint Strength

The bulk of the power generation during cycling comes from the knee and hip joints (Elmer et al., 2011). In a healthy male trained cyclist population, the hip, knee and ankle joints produced an average of 14%, 37% and 49% respectively of the total power during one pedal cycle at a workload of 250 W and 90 rpm (Elmer et al., 2011). Additionally, a MVIC for the ankle joint on the Biodex dynamometer is a comparatively more arduous task for participants than the hip or knee joints.

8.6 Descriptors

8.6.1 Age, Sex, Gender and Race

Age, sex, gender and race of the participants were obtained using a self-reported questionnaire. For sex, gender and race, response options included a self-describe and prefer not to report (see Appendix A, B, C).

8.6.2 Medication

The medication each participant was currently taking was obtained using a self-reported questionnaire (see Appendix L).

8.6.3 Segment Length, Height and Body Mass

Overall height and body mass was measured and recorded for each participant while they were wearing socks, a t-shirt and shorts using a stadiometer (see Appendix A). However, shank segment length and thigh segment length were measured and recorded for each participant while they were shod in an athletic shoe (see Appendix A). These segments lengths were measured with the motion capture system. The thigh segment was measured from the head of the femur to the midpoint between epicondyles of the knee and the shank segment was measured from the midpoint between epicondyle of the knee to the midpoint between malleoli.

8.6.4 Comorbidity

Using a self-reported questionnaire (see Appendix L) each participant's Charlson Comorbidity Index was scored. This is a useful method of estimating a participant's risk of mortality within the next 10 years (Charlson et al., 1987).

8.6.5 Knee OA Symptom Severity and Function

The Knee Injury and Osteoarthritis Outcome Scale (KOOS) was used to quantify the severity and function of each participant's knee symptoms (see Appendix F). The KOOS is a self-report questionnaire that evaluates the short and long-term knee-related outcomes in people with knee injury, knee OA or both (Collins et al., 2016; Roos & Lohmander, 2003). It has 42-items split into five separately scored subscales: Pain (nine items), Symptoms (seven items), Activities of Daily Living (17 items), Sport and Recreation Function (five items), and Knee-related Quality of Life (four items) (Collins et al., 2016; Roos & Lohmander, 2003). Each item is scored on a five-point Likert scale from 0 to 4, which are summed into subscale scores and then transformed to a 0 (extreme knee problems) to 100 (no knee problems) scale (Roos & Lohmander, 2003).

Reliability and Validity. Using pooled data from 26 different studies with participants with knee injury, knee OA or both, all the KOOS subscales demonstrated good-excellent test-retest reliability (ICC range 0.83-0.90) and good construct validity when correlated to the SF-36 subscales (r = 0.62 for KOOS Pain vs SF-36 Bodily Pain, r = 0.67 for KOOS Activities of Daily Living vs SF-36 Physical Function and r = 0.54 for KOOS Sport and Recreation Function vs SF-36 Physical Function) (Collins et al., 2016).

8.6.6 6-minute Walk Test

Osteoarthritis Research Society International (OARSI) has recommended the use of the 6-minute walk test (6MWT) to assess physical function in people with hip or knee OA (Dobson et al.,

2013). Physical function is defined as one's ability to move around and perform daily activities. During the 6MWT, participants walked as far as possible in six minutes around a 40.4m circuit at a self-selected pace. Though they were not allowed to run or jog, they were allowed to slow down, stop or sit down and time continued if the participant stopped (see Appendix G) (Dobson et al., 2013) Along the circuit, two standard chairs with arm rests were available for a rest.

Reliability and Validity. The 6MWT produces scores that show excellent test-retest reliability for those with primary OA (ICC = 0.991). The 6MWT also produces scores that showed good concurrent validity in relation to the KOOS subscales: Pain, r = 0.605; Symptoms, r = 0.397; Activities of Daily Living, r = 0.364; Sport and Recreation Function, r = 0.521; and Quality of Life, r = 0.758 (Ateef et al., 2016).

8.7 Cycling Bout Data Processing

The steps taken to process the kinematic and kinetic data from each bout of cycling are summarized in Figure 8. First, the kinematic data from Optotrak was combined with the kinetic data from the Forped pedals using a combination of custom and open-source Python code (Chénier, 2021). The combined data was imported into Visual3D where the data were filtered and a model of the lower limbs and pedals was constructed. The hip joint centers (both left and right) of 13 participants were located using functional hip joints, while the hip joint centers (both left and right) of 13 participants were located using the CODA (Codamotion Ltd., UK) hip joints. CODA hip joints were only used when Visual3D was unable to calculate hip joint power, due to Visual3D deeming the radius (distance between functional hip joint center and landmarked greater trochanter) of functional hip joint too small. Though the function hip joint produces a more accurate hip joint location, both methods are valid tools to find the hip joint center, both are commonly used in biomechanical models and the difference between CODA and functional hip joint locations is well

under the clinically relevant threshold for hip joint center mislocation error of 30mm (Fiorentino et al., 2016; Stagni et al., 2000). The coordinate systems used in the inverse dynamics calculation, and also used to determine the joint angles, were relative to each participant's foot, shank, thigh and pelvis segments, along with the pedals. Sixty full pedal cycles (approximately one minute) from each two-minute bout were averaged to one pedal cycle in Python (Gatti et al., 2021; Gatti & Maly, 2019). To accomplish this, 60 revolutions were selected based on a visual inspection of the bilateral joint angle and joint power data of each full bout for each hip, knee and ankle. A section (most often continuously, but a few were broken into two sections) from each bout with the most consistent amplitudes was selected. This average pedal cycle was used to represent the bout and was graphed using Python. Mean power and excursion were taken from these average pedal cycles and used in the statistical analyses.

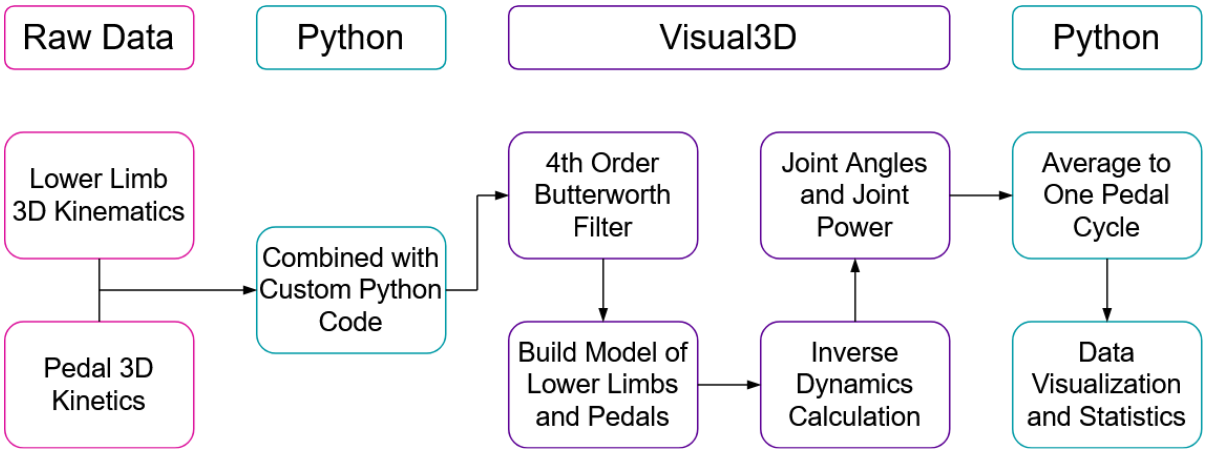


Figure 8 - Cycling bout data processing steps

Ensemble averages for hip, knee and ankle joint powers were calculated by averaging the average pedal cycle for each bout by condition for all participants and sorted by dominant and non-dominant sides (see Figures 12, 13 and 14).

8.8 Statistical Analyses

The Python packages SciPy and Statsmodels were used to first check the data for normality and outliers. Then, Python was used to run the two-factor analysis of covariance (ANCOVA) for the primary objective (using hip strength difference, knee strength difference and self-reported pain after cycling bouts as covariates). Python was also used to run the regression analyses for the secondary and tertiary objectives.

8.8.1 Primary Objective

A two-factor ANCOVA compared bilateral difference in each hip, knee and ankle joint power at the three seat heights (40°, 30°, 20°) and two workloads (40W, 75 W) after adjusting for strength and pain (see Table 3). Power at each joint was calculated as the mean joint power (average of both powers absorbed and produced) over an averaged pedal cycle. The difference in mean joint power was represented as a difference between dominant and non-dominant sides.

$$Bilateral\ Joint\ Power\ Difference\ (W) = (Dominant\ Side\ Mean\ Joint\ Power) - (Non - Dominant\ Side\ Mean\ Joint\ Power) \quad Equation\ 2$$

The data was represented as a pie chart, where the whole pie represents the total power over a single average pedal cycle. There were six pieces of pie, each representing the proportion of mean joint power from each hip, knee and ankle.

The covariates bilateral hip and knee strength, along with self-reported knee pain were represented as differences, similar to Equation 2.

Table 2 - List of variables of interest for the study procedure

Variables of Interest	Measurement
Dependent Variables	Bilateral Hip, Knee and Ankle Joint Power Difference Bilateral Hip, Knee and Ankle Joint Excursion Difference
Independent Variables	Seat Height Workload
Covariates	Bilateral Hip and Knee Strength Difference Bilateral Self-reported Knee Pain Difference
Descriptors	Age, sex, gender, race, medication, body mass, height, thigh segment length, shank segment length, Charlson Comorbidity Index, KOOS, 6-minute Walk Test

Table 3 – The conditions, covariates and dependent variables input into an analysis of covariance to address the primary objective.

Condition 1 - Seat Height	Condition 2 - Workload	Covariates	Dependent Variables
40° Knee Flexion Angle 30° Knee Flexion Angle 20° Knee Flexion Angle	40W 75W	Bilateral Knee Strength Difference Bilateral Hip Strength Difference Bilateral Self-reported Knee Pain Difference	Bilateral Hip, Knee and Ankle Joint Power Difference

8.8.2 Secondary Objective

Several mixed effect linear regressions were run to determine the amount of variance in bilateral joint power difference (represented as mean joint power dominant side minus non-dominant over an average pedal cycle) was explained by seat height, workload and the difference in bilateral knee pain. Separate regressions were run for each hip, knee and ankle joint power difference, along with leg power difference. The z-value represents how different the slope of the linear regression differs from zero.

8.8.3 Tertiary Objective

Several mixed effect linear regressions were run to determine the amount of variance in bilateral joint excursion (difference between maximum and minimum peak flexion angle) difference (represented as dominant side joint excursion minus non-dominant over an average pedal cycle) explained by seat height, workload and the difference in bilateral knee pain. Separate regressions were run for each of hip, knee and ankle joint excursion difference. The z-value represents how different the slope of the linear regression differs from zero.

8.8.4 P-value Correction

The Bonferroni method was used to correct the p-value for each objective based on repeated comparisons. The correction for the primary and secondary objectives was combined, because both objectives had the same dependent variable - joint power. The p-value for these objectives was corrected to 0.004 to account for the three ANCOVAs in the primary objective and eight regressions in the secondary objective. A separate correction was made for the tertiary objective, because it had a different dependent variable - joint excursion. The p-value for the tertiary objective was corrected to 0.008 to account for the six linear regressions.

9 Results

9.1 Participants Description

Of the 26 participants, one was left leg and 25 were right leg dominant. Equal numbers (13 and 13) identified as female/women and male/man. A total of 23 identified as White, two as South Asian and one as Black. From the comorbidity questionnaire given to participants, 14 reported having osteoarthritis, six back pain, four high blood pressure, two heart disease, two kidney disease, two hypothyroid and other issues such as lung disease, diabetes, anemia, osteoporosis were each reported once. From the medication questionnaire given to participants, nine reported taking ibuprofen, seven cholesterol-lowering agents, six Tylenol, plus four acetaminophen, four calcium channel blockers, three aspirin, three Synthroid, two Advil, two glucosamine and other medications such as ACE inhibitors, ARBs, blood thinners, blood pressure reducers, anti-inflammatories or medication for diabetes were each reported once. Of the 14 participants with a knee pain difference (in a minimum of two bouts) 10 had greater knee pain intensity in their dominant leg, three in their non-dominant leg and one in both, depending on the bout. Of the 12 participants with no pain difference, five reported having daily knee pain, one reported having knee pain in the past week and four reported having knee pain in the past month. Further participant description is provided in Table 4. As well, Table 5 provides details of the assessment of painful arcs observed across one revolution of the pedal.

Table 4 – Participant Descriptors – BMI (Body Mass Index), 6MWT (6-Minute Walk Test), KOOS (Knee Injury and Osteoarthritis Outcome Score), MVIC (Maximum Voluntary Isometric Contraction)

	All (n=26)				No Pain Difference (n=12)				Pain Difference (n=14)			
Variable	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
Age (y)	64.3	7.3	47	73	61.9	7.0	47	73	66.4	4.9	59	72
Body Mass (kg)	76.6	13.6	49.7	97.7	78.8	15.7	52.5	97.7	74.8	11.8	49.7	96.5
Height (m)	1.68	0.09	1.52	1.85	1.69	0.10	1.54	1.85	1.67	0.08	1.52	1.80
BMI (kg/m^2)	27.00	4.09	19.20	37.46	27.38	4.49	22.03	37.46	26.68	3.85	19.20	32.33
Dominant Thigh Segment Length (m)	0.44	0.03	0.39	0.50	0.45	0.03	0.39	0.50	0.44	0.02	0.40	0.47
Non-dominant Thigh Segment Length (m)	0.45	0.03	0.39	0.53	0.45	0.04	0.39	0.53	0.44	0.03	0.40	0.48
Dominant Shank Segment Length (m)	0.40	0.03	0.14	0.46	0.40	0.03	0.37	0.44	0.40	0.04	0.31	0.46
Non-dominant Shank Segment Length (m)	0.40	0.03	0.33	0.45	0.40	0.03	0.33	0.44	0.40	0.03	0.34	0.45
6MWT Distance (m)	554.6	78.06	343.4	666.6	547.3	92.5	343.4	648.6	560.8	66.3	483.0	666.6
KOOS Score (%)	75.1	17.5	44	100	83.0	16.8	45	100	68.3	15.5	44	95
MVIC Dominant Knee (Nm/kg)	1.87	0.53	0.55	2.92	1.90	0.59	0.55	2.92	1.84	0.48	1.17	2.63
MVIC Non-dominant Knee (Nm/kg)	1.83	0.48	0.72	2.70	1.83	0.57	0.72	2.70	1.82	0.41	1.17	2.46
MVIC Dominant Hip (Nm/kg)	2.23	0.48	1.09	3.18	2.14	0.53	1.09	3.18	2.32	0.41	1.43	3.01

MVIC Non-dominant Hip (Nm/kg)	2.26	0.55	1.13	3.45	2.19	0.67	1.13	3.45	2.32	0.44	1.76	3.07

Table 5 - Location of Painful Arc and motor control strategy of the hips, knees and ankles. More painful side is the side with higher knee pain intensity (of the 14 participants with a pain intensity difference between knees, 11 of them completed the painful arc protocol, while three were unsure where their knee pain started and ended or did not consider their knee pain persistent). More power means greater mean joint power than other side. Numbers in the mean joint power columns represent the total number of bouts participants have greater mean joint power in one side than the other.

Painful Arc Location	Number of Participants	Ankle		Knee		Hip	
		More Painful Side / More Power	Less Painful Side / More Power	More Painful Side / More Power	Less Painful Side / More Power	More Painful Side / More Power	Less Painful Side / More Power
Power Phase	5	6	23	13	17	12	18
Top-dead Center	1	6	0	0	6	6	0
Bottom-dead Center / Recovery Phase	3	0	17	15	2	5	12
Persistent	2	5	6	12	0	0	12
Total	**11**	**17**	**46**	**40**	**25**	**23**	**42**

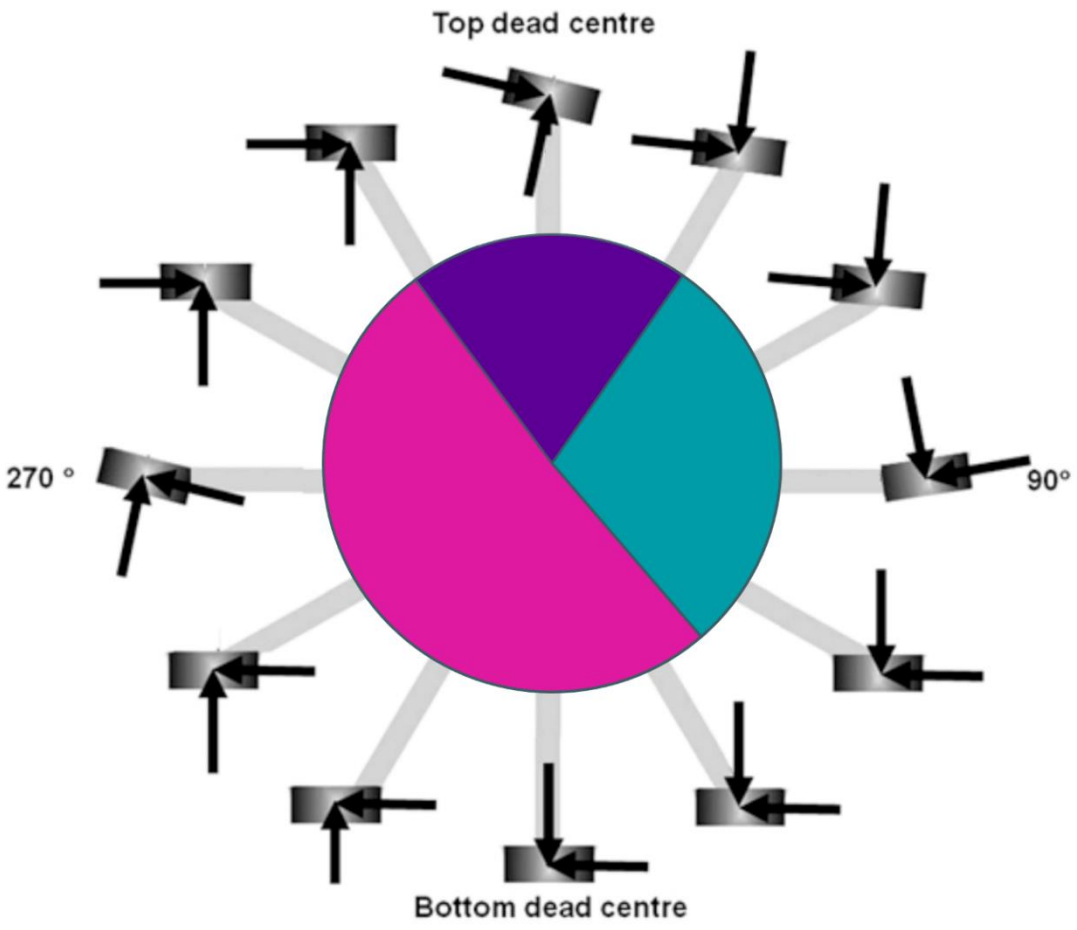


Figure 9 - Painful arc regions – purple is around top dead center, teal is during the power phase and pink is around bottom dead center thru the recovery phase. Image modified from Bini & Carpes, 2014.

9.2 Data Description

The normality of the hip, knee and ankle joint power difference data was checked using the Python packages SciPy and Statsmodels and visualized with histograms (Figure 10) and Q-Q plots (Figure 11). The ankle joint power difference had a skew of 1.67 (data has left skew) and kurtosis of 5.93 (data has high point). Also, one participant had an atypical ankle power difference compared to the rest of the participants and this led to the tail in the data. Though this could be considered an outlier, the data was considered clinically relevant, because this data was not believed to be driven by equipment error. The knee joint power difference had a skew of -0.15 (data has slight right skew) and a kurtosis of -0.15 (data is slightly flat and spread out). The hip joint power difference had a

skew of -0.12 (data has slight right skew) and kurtosis of -0.50 (data is slightly flat and spread out). A total of 152 bouts of cycling were completed by the 26 participants.

One participant had a modified protocol, because they were not able to complete a full two-minutes of the three bouts they attempted. One bout from another participant wasn't used because some marker data was missing over the full length of the bout. Only 30 revolutions from two bouts by two other participants were used because of an equipment error.

Ensemble joint power averages are shown in Figures 12, 13 and 14. These figures show that joint power at knees and hips increased with increasing workload, but not seat height. While joint power at the ankles increased with both increasing workload and increasing seat height. Means of the ensemble joint power averages are shown in Figure 15 and provides insight into the how the proportional contribution of each joint is only slightly affected by a change in seat height or workload. Figures 21 and 23 in Appendix M show joint power for typical participants. The participant in Figure 21 had no knee pain and the participant in Figure 23 had knee pain in their right knee (dominant leg). Figures 22 and 24 in Appendix M show joint angles for the same typical participants.

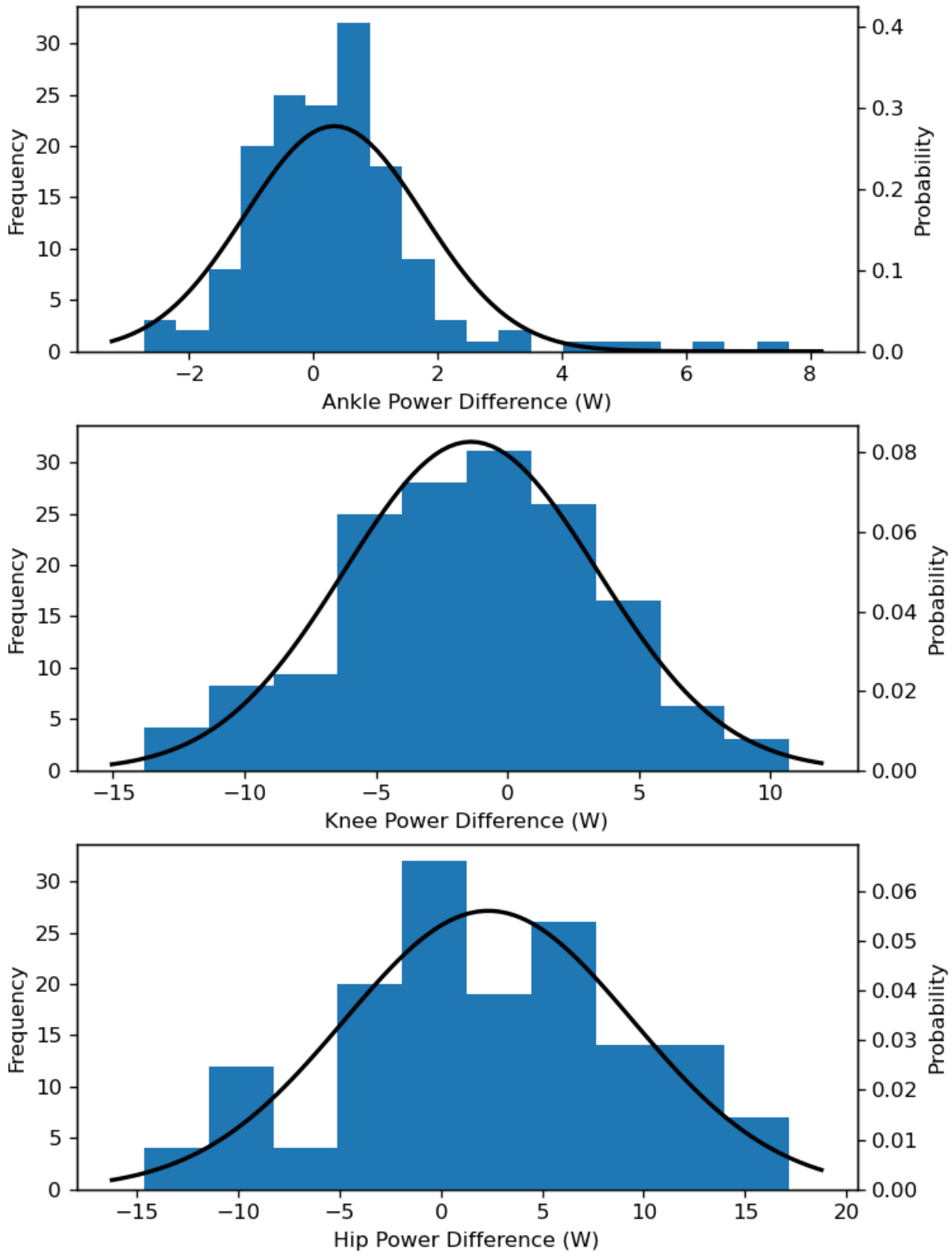


Figure 10 - Histograms for joint power difference at the hip, knee and ankle joints. Bins were set using the Freedman Diaconis Estimation

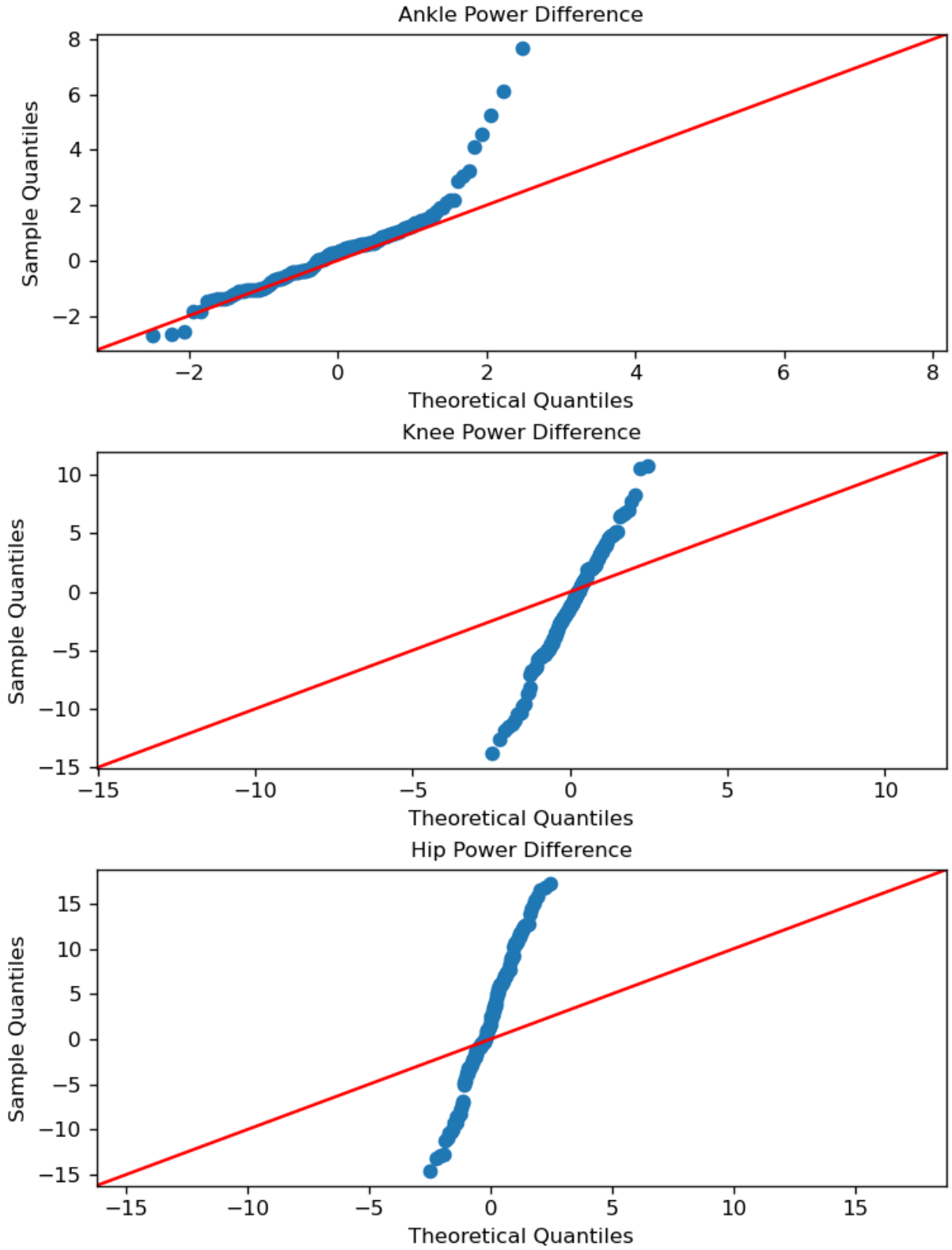


Figure 11 - Q-Q Plots for joint power difference at the hip, knee and ankle joints

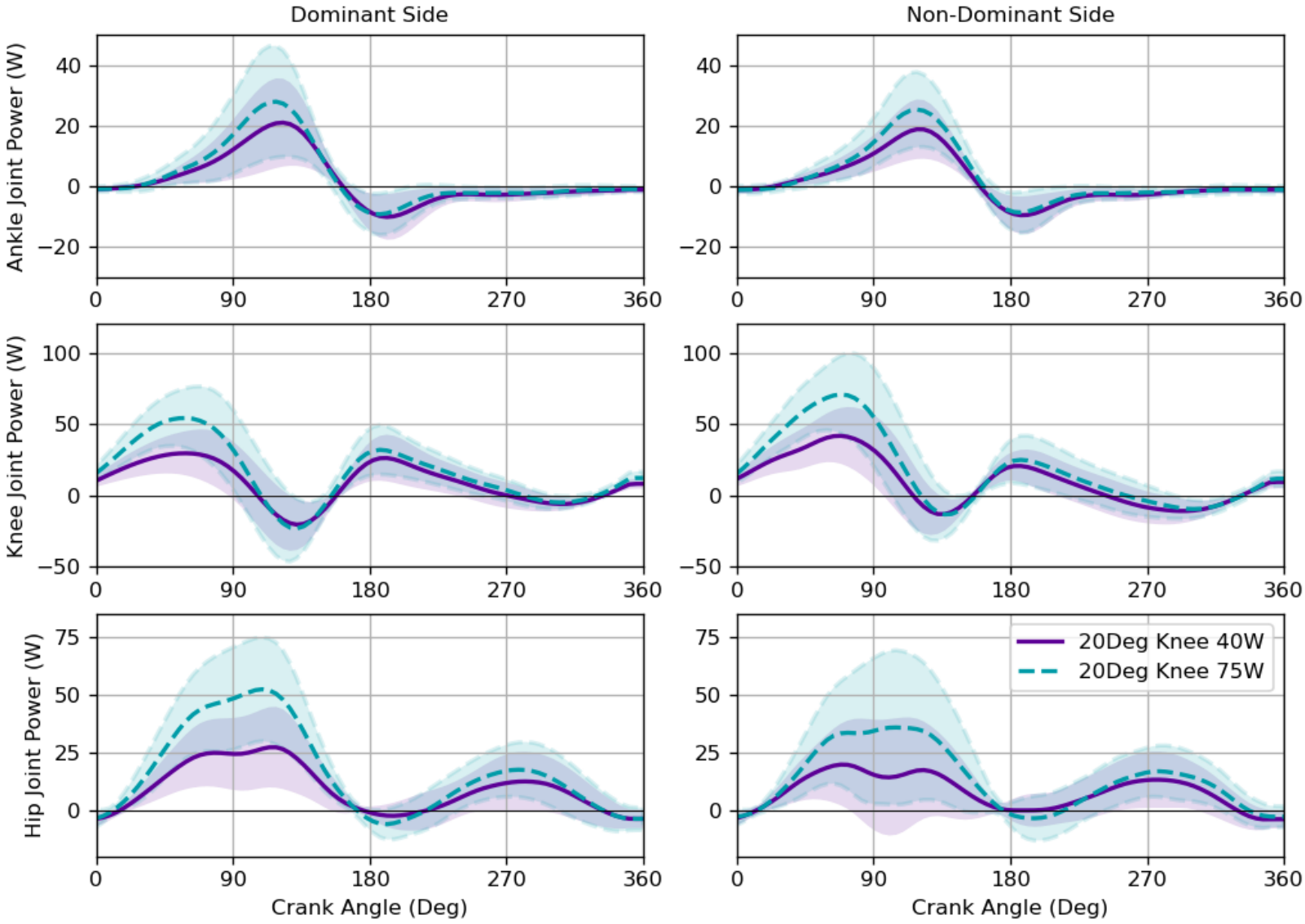


Figure 12 – Ensemble joint power for all participants at 20° knee flexion seat height

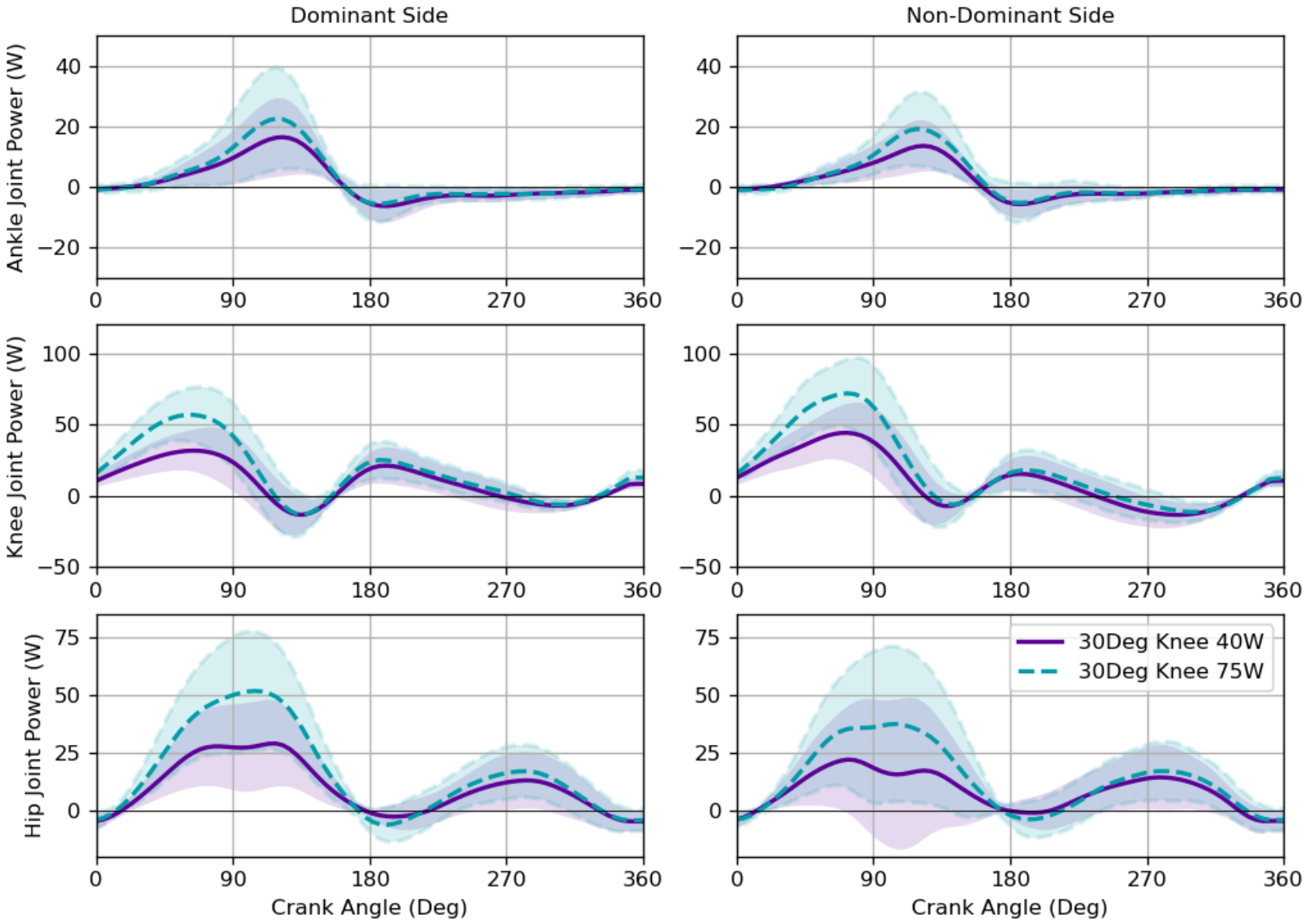


Figure 13 - Ensemble joint power for all participants at 30° knee flexion seat height

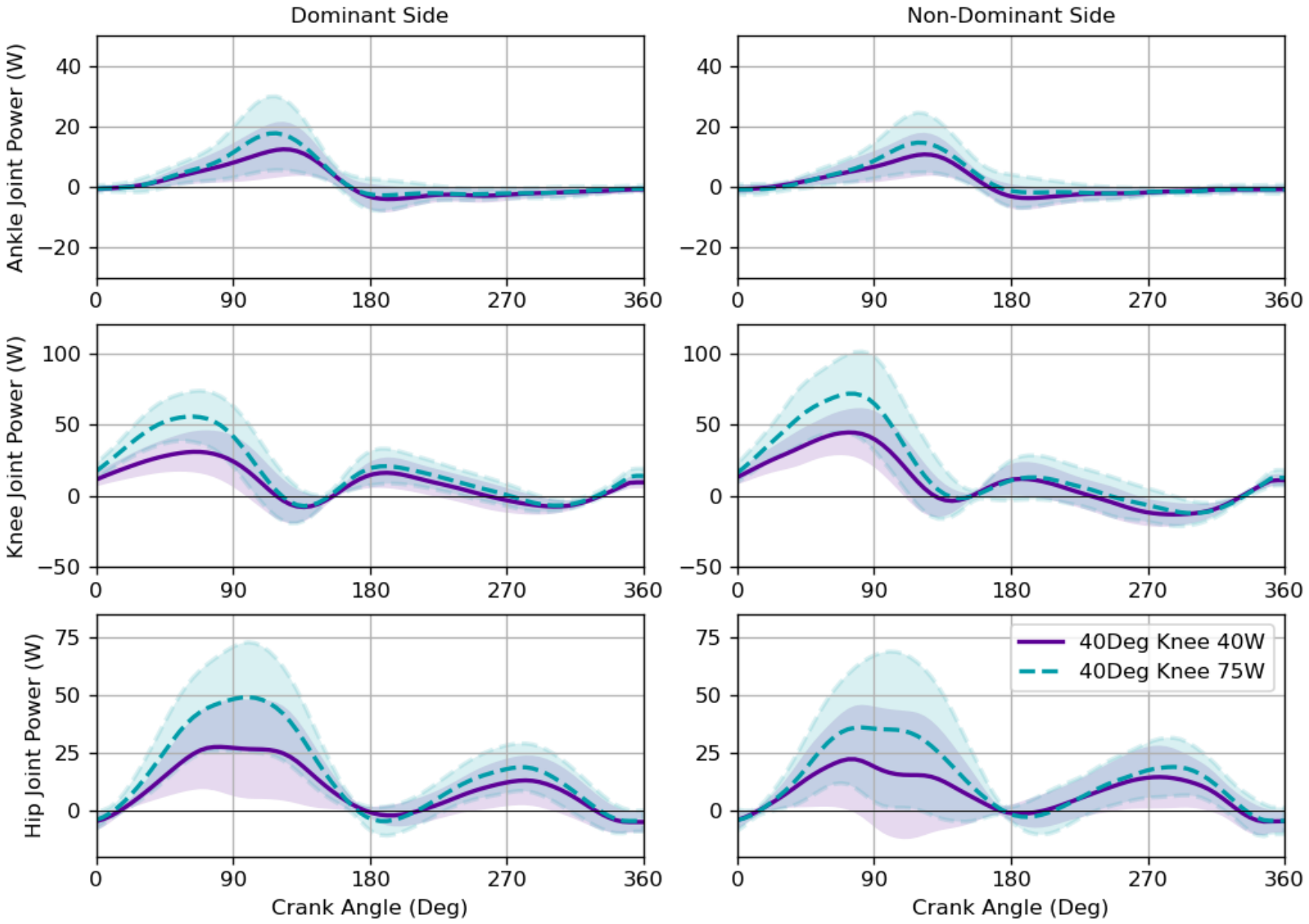


Figure 14 - Ensemble joint power for all participants at 40° knee flexion seat height



Figure 15 – Mean ensemble joint power for all participants – Visually, this shows very slight changes in joint power contribution. Ankle contribution increased as workload and seat height increased. Knee contribution increased as workload increased and seat height decreased. Also, hip contribution decreased as workload increased and was unaffected by seat height changes. Additionally, the dominant leg produced slightly more total joint power than the non-dominant at the 75W workload than the 40W workload.

9.3 Primary Objective Results

The ANCOVAs showed no significant effect of seat height, workload or their interaction on joint power difference after controlling for knee pain intensity difference, normalized hip extensor strength difference and normalized knee extensor strength difference at the ankles $F(8, 143) = 8.302$, $p > 0.004$ (Table 6), at the knees $F(8, 143) = 3.308$, $p > 0.004$ (Table 7) and at the hips $F(8, 143) = 8.302$, $p > 0.004$ (Table 8). The knee pain intensity difference covariate showed a significant relationship to joint power difference at the hips, knees and ankles ($p < 0.004$) (Tables 6, 7 and 8). This relationship will be detailed in the secondary objective. Additionally, hip extensor strength difference showed a significant relationship to knee joint power difference ($p < 0.004$) (Table 7).

Data used in the ANCOVAs (and the in the regressions for the secondary and tertiary objectives) is shown in the tables in Appendix M.

Table 6 - ANCOVA table for ankle power difference showing that the covariate knee pain intensity difference was significant ($p < 0.004$), shown in bold.

	Coefficient	Standard Error	t-statistic	P-value	Confidence Interval	
					0.025	0.975
Intercept	0.6051	0.249	2.428	0.016	0.112	1.098
Independent Variables						
Workload 75W	0.0822	0.346	0.238	0.813	-0.602	0.766
Seat Height 30°	-0.1036	0.346	-0.299	0.765	-0.788	0.581
Seat Height 40°	-0.1243	0.343	-0.363	0.717	-0.802	0.553
Interactions						
Workload x Seat Height 75W x 30°	0.1391	0.487	0.286	0.776	-0.824	1.102
Workload x Seat Height 75W x 40°	0.0717	0.487	0.147	0.883	-0.891	1.034

Covariates						
Knee Pain Intensity Difference	-0.6253	0.080	-7.810	**0.000**	-0.784	-0.467
Hip MVIC Difference	0.0007	0.409	0.002	0.999	-0.808	0.809
Knee MVIC Difference	0.0394	0.331	0.119	0.905	-0.615	0.694

Table 7 - ANCOVA table for knee power difference showing that the covariates knee pain intensity difference and hip MVIC difference were both significant (p < 0.004), shown in bold.

	Coefficient	Standard Error	t-statistic	P-value	Confidence Interval	
					0.025	0.975
Intercept	-1.8929	0.931	-2.034	0.044	-3.733	-0.053
Independent Variables						
Workload 75W	-1.0402	1.292	-0.805	0.422	-3.595	1.514
Seat Height 30°	0.1825	1.294	0.141	0.888	-2.374	2.739
Seat Height 40°	-0.2229	1.280	-0.174	0.862	-2.753	2.307
Interactions						
Workload x Seat Height 75W x 30°	0.7599	1.819	0.418	0.677	-2.835	4.355
Workload x Seat Height 75W x 40°	0.8928	1.819	0.491	0.624	-2.702	4.488
Covariates						
Knee Pain Intensity Difference	1.2752	0.299	4.265	**0.000**	0.684	1.866
Hip MVIC Difference	5.0512	1.528	3.306	**0.001**	2.031	8.071
Knee MVIC Difference	1.1668	1.236	0.944	0.347	-1.276	3.610

Table 8 - ANCOVA table for hip power difference showing that the covariate knee pain intensity difference was significant (p < 0.004) , shown in bold.

	Coefficient	Standard Error	t-statistic	P-value	Confidence Interval	
					0.025	0.975
Intercept	2.7012	1.234	2.188	0.030	0.261	5.141

Independent Variables						
Workload 75W	1.9599	1.714	1.143	0.255	-1.428	5.348
Seat Height 30°	0.1904	1.716	0.111	0.912	-3.201	3.582
Seat Height 40°	0.0638	1.697	0.038	0.970	-3.291	3.419
Interactions						
Workload x Seat Height 75W x 30°	-0.6565	2.412	-0.272	0.786	-5.425	4.112
Workload x Seat Height 75W x 40°	-0.1883	2.412	-0.078	0.938	-4.957	4.580
Covariates						
Knee Pain Intensity Difference	-2.9988	0.397	-7.562	**0.000**	-3.783	-2.215
Hip MVIC Difference	-0.7952	2.026	-0.392	0.695	-4.801	3.210
Knee MVIC Difference	2.0230	1.639	-1.234	0.219	-5.263	1.217

9.4 Secondary Objective Results

Since seat height did not produce joint power differences between the dominant and non-dominant legs (at hips, knees or ankles), these data were collapsed together for analyses of the relationship between a difference in knee pain intensity and joint power differences. Workload also did not produce a difference but was not collapsed, because hip, knee and ankle joint powers were consistently higher at 75W compared to 40W on visual inspection (Figures 12, 13 and 14). As shown in Figure 16, there are significant relationships between joint power difference and knee pain intensity difference at the ankles (40W workload $z = -5.983$, $p < 0.004$, 75W workload $z = -5.316$, $p < 0.004$), knees (75W workload $z = 2.993$, $p < 0.004$), hips (40W workload $z = -5.164$, $p < 0.004$, 75W workload $z = -5.523$, $p < 0.004$) and total leg (40W workload $z = -5.615$, $p < 0.004$, 75W workload $z = -5.212$, $p < 0.004$), which is the sum of hip, knee and ankle joint power differences.

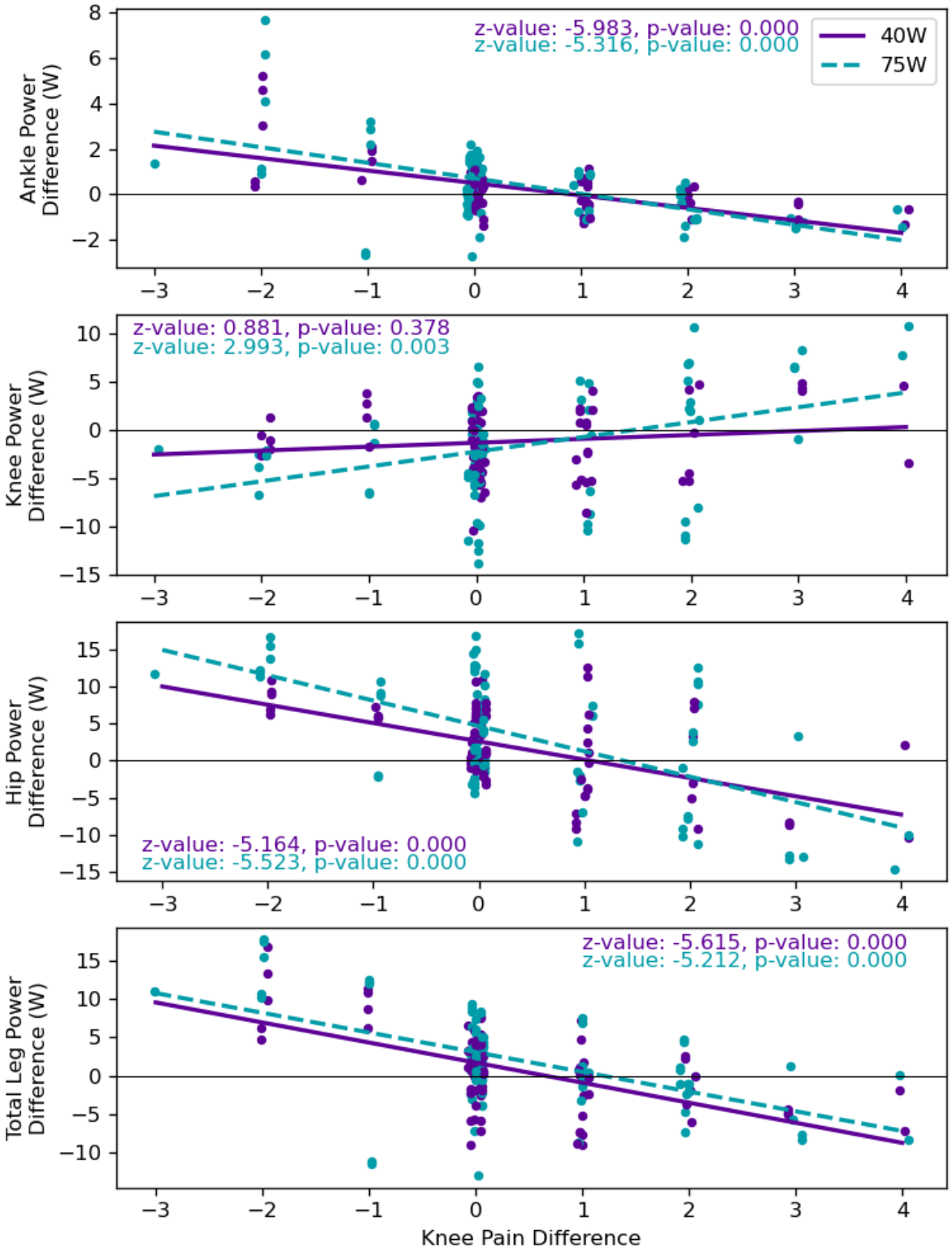


Figure 16 - Difference in power at ankles, knees, hips and total leg (sum of all 3 joints) compared to difference in knee pain intensity. Difference is dominant side minus non-dominant size. Positive values mean more power or pain in dominant side. A positive slope means power difference is increasing with increasing knee pain difference, while a negative slope means power difference is decreasing with increasing knee pain difference. Each data point represents one bout from one participant. Seat heights have been collapsed into the two workloads. Significant if p<0.004.

9.5 Tertiary Objective Results

Similar to the secondary objective the seat height data were collapsed together for analyses of the relationship between a difference in knee pain intensity and joint excursion differences. Separate linear regressions comparing hip, knee and ankle joint flexion/extension excursion to knee pain intensity difference showed significant correlations at the ankle and knee joints. As shown in Figure 17, there are significant relationships between joint excursion difference and knee pain intensity difference at the ankles (40W workload $z = -5.788$, $p < 0.008$, 75W workload $z = -4.230$, $p < 0.008$), knees (40W workload $z = -2.972$, $p < 0.008$, 75W workload $z = -4.906$, $p < 0.008$). There is no significant relationship at the hip, but there does appear to be a very slight positive trend between hip excursion difference and knee pain intensity difference.

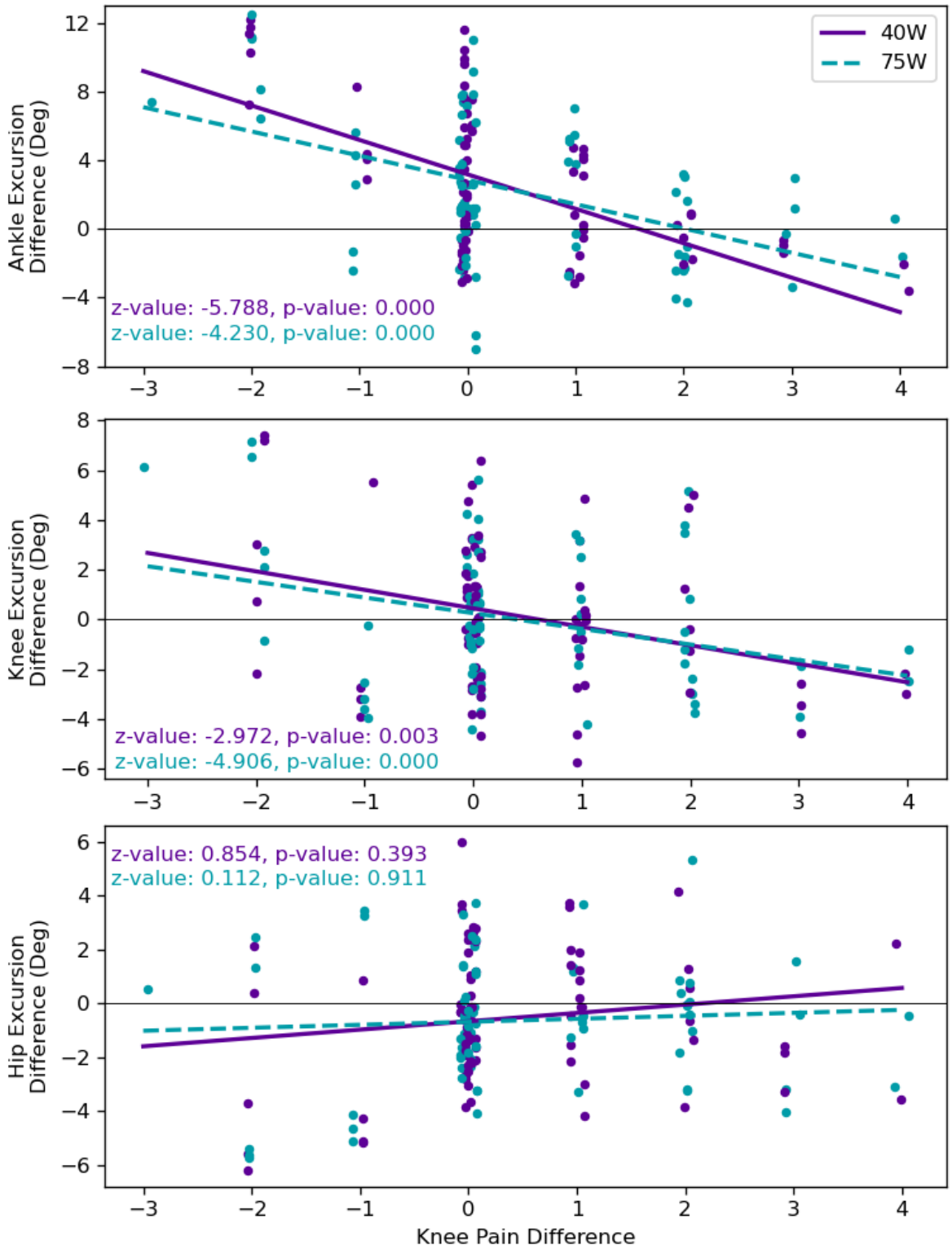


Figure 17 - Difference in joint excursion at ankles, knees and hips compared to difference in knee pain intensity. Difference is dominant side minus non-dominant size. Positive values mean more excursion or pain in dominant side. A positive slope means excursion difference is increasing with increasing knee pain difference, while a negative slope means excursion difference is decreasing with increasing knee pain difference Each data point represents one bout from one participant. Seat heights have been collapsed into the two workloads. Significant if p<0.008.

10 Discussion

The purpose of this study was to compare the symmetry of joint power at the hip, knee and ankle joints at different seat heights and workloads in people with and without knee pain due to knee OA. A secondary objective was to determine the relationship between joint power and knee pain. At each of the hip, knee and ankle joints, any difference in joint power between the dominant and non-dominant leg was unchanged by seat heights and workload. Significant relationships were found between hip, knee and ankle joint power difference and knee pain: the more painful knee produced more joint power than the less painful knee but, interestingly, the ankle and hip in the limb with the painful knee showed the opposite. In fact, the overall limb with the more painful knee produced less power than the limb with the less painful knee. A sample of recreational cyclists (aged 47-73, 21 with symptomatic knee OA in at least one knee) were recruited and measured for this study; therefore, these results can be applied to cycling for rehabilitation and are relevant to rehabilitation clinicians. If the treatment goal is for the patient to produce greater joint power, then the height of the seat should be set to the patient's comfort and the workload set as high as tolerable. This recommendation is based on the observation that seat height does not affect joint power difference and increasing workload leads to increased knee and hip joint power, but not greater asymmetry in joint power or joint excursion at the hip, knee and ankle.

10.1 Knee Pain Difference Versus Joint Power Difference

The more painful knee was producing more joint power than the less painful knee. This was a surprising result, because we expected the more painful joint to be working less due to arthrogenic inhibition (a neural inhibition that limits muscle activation (Rice et al., 2011)). Though the literature is mixed on whether or not arthrogenic inhibition reduces muscle activation of lower limb muscles in the leg with knee OA during exercise (Brenneman et al., 2016; Rice et al., 2011), the level of muscle

activation during the cycling bouts is not known. It is possible that due to the low workloads completed in the current study, the participants' lower limb muscles did not activate enough to experience arthrogenic inhibition.

With this study being cross-sectional, we do not know the direction of this association. It is possible that prior to the onset of knee pain the joint power difference existed (or was higher or lower). Also, it is possible that pain is driving the joint power difference. The presence of pain could cause the participant to focus on the joint, subconsciously push through the pain, leading to more joint power production. Leg dominance may play a role in knee pain as well. Most participants reported either knee pain only in their dominant leg or greater knee pain intensity in their dominant leg (n= 10 dominant leg knee pain of the 14 participants who reported a knee pain difference). Though it may seem logical that the dominant limb would have the more painful knee, leg dominance is not widely reported in studies of knee OA.

It is likely that several different motor control strategies by were used by the participants. For example, participants without knee pain or no pain difference had, in general, greater total leg power in their dominant leg. Breaking this down further, their dominant ankle and hip, along with non-dominant knee produced greater joint power than the contralateral joints. On the other hand, among participants with a pain difference, the leg with the more painful knee produced less total leg power than the leg with the less painful knee. It is interesting that the painful knee appeared to be the main contributor to power production across the limb. Given the number of muscles, along with kinematic and kinetic variables involved with the locomotion of the lower joints and limbs, there are likely multiple redundant strategies involved in performing the cycling task (D. A. Winter, 1984). This abundance of strategies could explain the low correlation observed between knee pain difference and knee joint power difference.

The results of this current study run contrary to Buddhadev et al., 2018 who concluded that the leg more affected by knee OA produced more power than the contralateral leg. This difference is likely due to the difference in study methods, because the sample participants in both studies were of similar mean age (67.3 years old versus 64.3 years old) and were recreational cyclists (average weekly cycling less than eight hours). A review of Buddhadev et al., 2018 study's methods indicated that self-reported knee pain intensity was recorded prior to cycling, while this current study recorded self-reported knee pain intensity after each round of cycling. During this study, six participants reported having daily knee pain or knee pain in the past week but experienced no pain or a zero-pain difference during the cycling bouts. In these cases, usually their dominant leg produced more power. In Buddhadev et al., 2018 the more affected knee was in the dominant leg for seven of 12 in their OA group. These opposite results are likely due to the participants with knee OA in Buddhadev et al., 2018 not having knee pain during the rounds of cycling. Additionally, the inconsistency in findings might also reflect that Buddhadev et al., 2018 included a sample size of 12, which may not reflect the broader population.

Though workload did not show a significant relationship to joint power difference, some participants experienced greater knee pain intensity at the 75W workload compared to the 40W workload. This makes sense, because greater knee flexion moment is related to greater knee pain intensity (Huang et al., 2021). It is possible a higher workload (e.g. 150W) would further increase knee pain intensity and therefore, joint power difference with it. Additionally, considering that the slope of the linear regression line is steeper for the 75W workload than the 40W (Figure 16), it's possible that a higher workload would lead to an even steeper slope, meaning joint power difference would increase (or decrease) at a higher rate with increasing knee pain difference.

Asymmetry was commonly observed across joints, regardless of pain difference, as shown in Figure 16. Few joint power difference values are zero. A review of the literature has shown that

bilateral asymmetry between total leg (or pedal) power can be as high as 20% in healthy adults, but bilateral joint asymmetry (or difference) has not been reported readily in cycling studies (Carpes et al., 2010). Cycling studies often collect unilateral data and assume joint symmetry or collect only pedal forces or pedal power without motion capture of the lower limbs (Bini & Hume, 2015; Buddhadev et al., 2018; Elmer et al., 2011; Verma et al., 2016). Smak et al., 1999 collected bilaterally and observed differences in bilateral knee flexor moment and hip extensor moment. Specifically, they noted a greater hip extensor moment in the dominant leg and greater knee flexor moment in the non-dominant leg (Smak et al., 1999). The results of this study observed a similar pattern, where, in most participants, when one knee (could be dominant or non-dominant) produced greater mean joint power, the contralateral hip produced greater mean joint power than the ipsilateral hip. Another interesting finding was that some participants produced most of their power with their hips, while others produced most of their power with their knees.

10.2 Knee Pain Difference Versus Joint Excursion Difference

Joint excursion in flexion/extension at ankles and knees decreased significantly as knee pain intensity increased. This same trend for knee excursion has been observed in patients with knee OA during walking, where pain intensity explained 18% of the variance in knee flexion/extension excursion (Maly et al., 2008). The current study observed a relatively weaker association between joint excursion and knee pain intensity compared to Maly and colleagues. This difference in explained variance between studies could be caused by several differences between the studies. First, the difference between the unconstrained gait task and the constrained cycling task (movement of the lower limbs during cycling is linked with the range of movement available to the pedals). The difference in how pain intensity was recorded (Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) versus NPRS after each bout). Lastly, the difference in

weight bearing between walking and cycling, where the bicycle seat supports much of the rider's body mass.

10.3 Painful Arc

Measuring where a participant experiences knee pain in pedal cycle is a relatively novel measurement. The participants' painful arcs were in one of three observed positions (and each range of painful motion does overlap): (1) within the power stroke where the pedal moves from top to bottom dead center, (2) from near bottom dead center where the knee is in maximum extension through the recovery phase and (3) around top dead center where the knee is in maximum flexion. Additionally, some participants experienced persistent knee pain through the full pedal cycle. The location of this painful arc (see Figure 9) may influence their motor control strategy as shown in Table 5. Though due to the small sample size at each painful arc location, it would be difficult to draw any conclusions. It appears there is greater variability in the contribution of knees and hips when the painful arc is in the power phase of the pedal stoke, but that could be due to this group having the largest sample.

There may be a relationship between location or size of the painful arc and peripheral and central pain sensitization. If the start of the painful arc is related to peripheral pain sensitization, the size, duration or intensity of the painful arc is likely related to central pain sensitization (Ohashi et al., 2023). Though since pain sensitization was not explored in this study, future research would be needed to determine the existence of a relationship.

There are other tests that measure painful arcs in the shoulder and knee joints. The Neer, Hawkins-Kennedy and painful arc tests are used in the diagnosis of subacromial impingement (Hegedus et al., 2012). A patellofemoral painful arc test demonstrated by Dughbaj et al., 2018 uses dynamic sonography to see soft tissue impingement at the patellofemoral joint. This patellofemoral

painful arc test by Dughbai and colleagues differs from the painful arc test in this current study because their test reflects a different joint and was performed unloaded for the purpose of identifying impingement of tissue.

10.4 Knee and Hip Strength

As shown in the ANCOVA for the knee (Table 7), there is a significant, positive relationship between knee joint power difference and normalized hip MVIC difference. It is possible the asymmetry of hip extensor strength is helping to drive the asymmetry of power at the knee joints, but it is also possible the asymmetry in knee joint power has led to asymmetry of hip extensor strength. Similar to the relationship between joint power and knee pain, we do not know the direction of this association.

There is no significant relationship between normalized knee MVIC and knee joint power difference. Also, there is no significant relationship between normalized knee or hip MVIC and ankle or hip joint power difference. It is possible a higher workload could have required the participants to use a greater amount of their knee and hip extensor strength, which could have led to a different finding regarding the relationship between strength and joint power or knee pain. It is also possible that the slight differences in strength between knees is due to the low level of pain in the sample. The average level of pain intensity reported in the more painful knee was a two on the NPRS.

As shown in Table 4, there was only a slight difference between dominant and non-dominant knee or hip extensor strength. The knee in the dominant leg had slightly higher mean normalized MVIC values (all: 0.04 Nm/kg higher, no pain difference: 0.07 Nm/kg higher, pain difference: 0.02 Nm/kg higher) than the knee in the non-dominant leg. Similarly, the hip in the non-dominant leg had nearly the same mean normalized MVIC values (all: 0.03 Nm/kg higher, no pain difference: 0.05 Nm/kg higher, pain difference: no difference in MVIC) compared with hip in the dominant leg.

However, when the participants with a pain difference are sorted by more versus less painful side a different trend appears. The more painful knee had slightly lower mean normalized MVIC values (1.80 Nm/kg) than the less painful knee (1.87 Nm/kg). While the hip in the leg with the more painful knee had slightly higher mean normalized MVIC values (2.37 Nm/kg) than the hip in the leg with the less painful knee (2.27 Nm/kg). A painful knee having reduced strength matches the literature, which has shown that lower knee extensor strength is associated with both an increased risk of symptomatic knee pain and a decline in knee function (Culvenor et al., 2017). The hip on the more painful side having greater strength than the opposite hip, suggests that the hip may be compensating for the painful knee. These findings were consistent with what has been found in previous studies, that increasing the strength of the painful knee could reduce the intensity of the knee pain (Escalante et al., 2010; Oiestad et al., 2023; Sharma, 2021).

10.5 Limitations

Post-hoc power analysis for the primary objective showed the sample size of this study (26 participants) was less than the required amount to achieve 80% power. This also means it is possible that the ANCOVA for the primary objective is over fit. However, post-hoc power analysis showed to achieve 80% power and 0.05 alpha for each of the ANCOVAs of the hip, knee and ankle 1363 participants would be needed for a significant finding of workload and 6719 participants would be needed for a significant finding of seat height. This rather large number of required participants suggests that there is no substantive relationship between workload and joint power difference or seat height and joint power difference. All that said, a review of the literature shows most biomechanics cycling studies have sample sizes between nine to 24 participants, with one reaching 40 participants (Bini et al., 2010; Buddhadev et al., 2018; Elmer et al., 2011; Gardner et al., 2015; Gatti et al., 2021; Hummer et al., 2021).

One unexpected outcome was participants self-reported less pain during cycling than during the screening call. Of the 26 participants in the study, 23 reported having knee pain during the screening call. However, during cycling only 14 self-reported a knee pain difference, which limited the number of non-zero knee pain difference data points collected. Additionally, the maximum knee pain difference reported was a four on the NPRS. Several factors could have led to this outcome. First, cycling has been shown to reduce knee pain, so it should not be surprising that some participants had less or no pain compared to what they reported during screening (Escalante et al., 2011). Relatively light workloads (40W and 75W) were selected for this study with the hope that all participants would be able to complete all bouts and that participants would not experience a high knee pain intensity (seven or greater on the NPRS). Participants who take medication to reduce the intensity of their knee pain were not asked to stop taking their medication before their visit to the lab. Lastly, participants could have been recruited from sources, such as a surgeon's office, who have patients with high knee pain intensity.

Another unexpected limitation of this study was an issue with calculating hip joint power in Visual3D. When the radius (distance between functional hip joint center and landmarked greater trochanter) of functional hip joint was deemed too small by Visual3D, it did not calculate the hip joint power. This issue was solved either by calculating the joint radius (distance between left and right hip joint centers divided by two, suggested by HAS Motion) instead of using the landmarked greater trochanter or calculating the joint radius and using the CODA hip joint centers instead of the functional joint centers. This means half of the participant's left and right hip joint centers were located using the functional joint centers and half of the participant's left and right hip joint centers were located using the CODA hip joint centers. Though the function hip joint produces a more accurate hip joint location, both methods are valid tools to find the hip joint center, both are commonly used in biomechanical models and the difference between CODA and functional hip joint

locations is well under the clinically relevant threshold for hip joint center mislocation error of 30mm (Fiorentino et al., 2016; Stagni et al., 2000).

10.6 Future Directions

Future research should explore the relationship between lower limb joint power during other tasks such as walking and stair climbing. It would be interesting to find out if the same significant relationship and motor control strategy observed during the constrained task of cycling, also appeared in unconstrained tasks. Additionally, participants with higher bilateral knee pain intensity differences, perhaps through surgical clinics, should be recruited in future studies. A more severe sample would inform if the relationship observed in this study holds true at higher pain intensities. Another option would be to use higher workloads (e.g. 150W or greater) as this could potentially increase the knee pain intensity experienced by participants.

Future work should include electromyography (EMG) to examine muscle activation. The inverse dynamics model in this study provided insight into joint kinematics and kinetics. The addition of EMG would show the muscle activation patterns of the lower limb muscles, which would provide deeper insight into the motor control patterns observed in this study.

A longitudinal study should be considered in future research to hopefully solve the “chicken or egg” question discovered in this study. This was a cross-sectional study and therefore it is not known if knee pain is driving the motor control strategy observed or if the motor control strategy came first. This longitudinal study would need to take place over years to see if participants who develop knee pain from OA have a significant change in their motor control strategy.

11 Conclusions

This study has demonstrated the relationship between lower limb joint power and knee pain during cycling and in turn, how these joints can contribute power in the presence of knee pain. Though the seat heights and workloads used in this study did not influence the symmetry of joint power, it was interesting to observe the relationship with knee pain and how the more painful knee produced more joint power than the less painful knee. Future work should explore the relationship between lower limb joint power and knee pain further using greater workloads, different tasks and patients with larger knee pain intensity differences.

12 Significance

12.1 Share of Power

This research has expanded the understanding of lower joint and limb power generation and range of motion during stationary cycling in people with unequal OA knee pain. It has filled knowledge gaps in joint power generation contribution and symmetry between joints and limbs during cycling. One important and unexpected finding was that the knee joint with painful OA produced more power than the less painful knee. This finding emphasizes that rehabilitation could aim to boost power produced by other joints to offload a symptomatic joint. Another perspective is that cycling can support the rehabilitation of a knee more affected by OA, because this knee produced more power than the less affected knee it still has the potential to build strength through cycling.

12.2 Symmetry versus Workload and Seat Height

This research has shown there is no effect of vertical seat height or workload on the symmetry of joint power. This finding is relevant to rehabilitation clinicians. If the treatment goal is for the patient to produce greater joint power, then the height of the seat should be set to the patient's comfort and the workload set as high as tolerable, because neither will change the proportion of joint power produced by a painful knee at submaximal cycling workloads.

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MOBILIZE CYCLING STUDY			
PARTICIPANT ID:		**DATE:**	(MM/DD/YYYY)

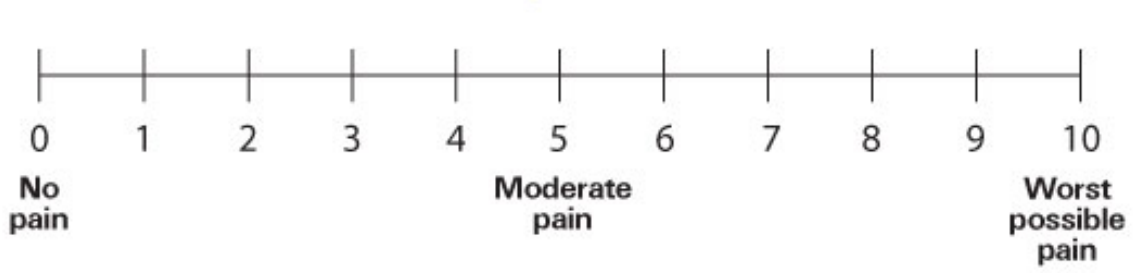
Appendices

Appendix A: Anthropometrics and Date of Birth

Participant should be barefoot or wearing socks, wearing a t-shirt and shorts.

Date of Birth (MM/YYYY)	
Mass (kg)	
Mass (lbs) (Note: for Biodex)	
Height (m)	
Body Mass Index (kg/m2)	
*Waist Circumference (cm)	
Dominant Leg	
Left Knee Pain (NPRS)	
Right Knee Pain (NPRS)	

*Measure <u>waist circumference</u> at the point that is midway between iliac crest and lower rib margin, on maximal expiration.



MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Appendix B: Demographic Data Collection – Sex and Gender

What is your sex assigned at birth?

- ☐ Prefer not to disclose
- ☐ Female
- ☐ Male
- ☐ Intersex
- ☐ Not listed

If you chose “not listed", please indicate your answer below:

_____

What is your current gender identity?

- ☐ Prefer not to disclose
- ☐ Woman
- ☐ Man
- ☐ Non-binary
- ☐ Prefer to self-describe

If you chose “prefer to self-describe", please indicate your answer below:

_____

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Appendix C: Demographic Data Collection - Race

We aim to engage people of different races when studying health. Collecting this information will help us monitor and ensure diversity is represented in our studies.

We invite you to choose what best describes you: please **check all** that apply.

		Examples
☐	Black	African, Caribbean, Black Canadian, Afro-Latine, African American, or other African descent
☐	East Asian	Chinese, Korean, Japanese, or other East Asian descent
☐	Indigenous	First Nations, Métis, or Inuit
☐	Latine/Latinx	Latin American, Hispanic descent
☐	Middle Eastern	Afghan, Egyptian, Iranian, Lebanese, Turkish, Kurdish, or other Arab or Persian descent
☐	South Asian	East Indian, Pakistani, Bangledeshi, Sri Lankan, Indo-Caribbean, or other South Asian descent
☐	Southeast Asian	Filipino, Vietnamese, Cambodian, Thai, Malaysian, Indonesian, or other Southeast Asian descent
☐	White	British, German, Ukrainian, or other European descent
☐	Another race category	Not described above
☐	Do not know	
☐	Prefer not to answer	
☐	Prefer to self-describe	

If you chose “prefer to self-describe", please indicate your answer below:

_____

MOBILIZE CYCLING STUDY			
PARTICIPANT ID:		**DATE:**	(MM/DD/YYYY)

Appendix D: Bicycling Experience

What type of bicycle do you ride? (Circle all that apply)

Road	Stationary	E-bike	None

In the past year, on average how long (hours) did you ride your bicycle(s) in 1 week?

Road	Stationary	E-bike

For how many years have you been riding your bicycles(s)?

Road	Stationary	E-bike

How many months in a year do you ride your bicycle(s)?

Road	Stationary	E-bike

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Appendix E: Screening Form

Participant is/has:

- ○ Adult aged 45-75 years of age
- ○ Either self-report knee pain or no knee pain
- ○ If knee pain is reported, meet the American College of Rheumatology clinical criteria for knee OA*
    - ○ Knee pain on most days of the month and **at least 3 of the following**:
        - ○ 50 years of age or older;
        - ○ stiffness lasting fewer than 30 minutes;
        - ○ crepitus;
        - ○ bony tenderness;
        - ○ bony enlargement;
        - ○ no palpable warmth
- ○ Complete and pass the Get Active Questionnaire.

Participant is not/does not have:

- ○ Other form of arthritis
- ○ Engaged in cycling races within the past year
- ○ Cycle 8 or more hours per week within the past year
- ○ Active non-arthritic knee disease (e.g., gout)
- ○ Condition that could exacerbated by protocol (such as exercise)
- ○ Past hip, knee or ankle surgery or joint replacement
- ○ Weigh more than 250lbs (stationary bike limit)
- ○ Lower extremity injury within 6 months and actively in rehab
- ○ Hip or ankle conditions (e.g., OA, rheumatoid arthritis)
- ○ Self-report high knee pain (7 or more on the NPRS)

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Appendix F: Knee injury & Osteoarthritis Outcome Score

This survey asks for your view about your knee. This information will help us keep track of how you feel about your knee and how well you are able to perform your usual activities.
Answer every question by ticking the appropriate box, only one box for each question. If you are unsure about how to answer a question, please give the best answer you can.

Symptoms

These questions should be answered thinking of your knee symptoms during the **last week**.

S1. Do you have swelling in your knee?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S3. Does your knee catch or hang up when moving?

Never	Rarely	Sometimes	Often	Always
☐	☐	☐	☐	☐

S4. Can you straighten your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

S5. Can you bend your knee fully?

Always	Often	Sometimes	Rarely	Never
☐	☐	☐	☐	☐

Stiffness

The following questions concern the amount of joint stiffness you have experienced during the **last week** in your knee. Stiffness is a sensation of restriction or slowness in the ease with which you move your knee joint.

S6. How severe is your knee joint stiffness after first wakening in the morning?

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Pain

P1. How often do you experience knee pain?

Never ☐ Monthly ☐ Weekly ☐ Daily ☐ Always ☐

What amount of knee pain have you experienced the **last week** during the following activities?

P2. Twisting/pivoting on your knee

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P3. Straightening knee fully

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P4. Bending knee fully

None Mild Moderate Severe Extreme

☐	☐	☐	☐	☐

P5. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P6. Going up or down stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P7. At night while in bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P8. Sitting or lying

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

P9. Standing upright

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, daily living

The following questions concern your physical function. By this we mean your ability to move around and to look after yourself. For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A1. Descending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A2. Ascending stairs

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

A3. Rising from sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A4. Standing

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A5. Bending to floor/pick up an object

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A6. Walking on flat surface

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A7. Getting in/out of car

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A8. Going shopping

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A9. Putting on socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A10. Rising from bed

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A11. Taking off socks/stockings

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A12. Lying in bed (turning over, maintaining knee position)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A13. Getting in/out of bath

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A14. Sitting

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A15. Getting on/off toilet

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

A17. Light domestic duties (cooking, dusting, etc)

None	Mild	Moderate	Severe	Extreme
☐	☐	☐	☐	☐

Function, sports and recreational activities

The following questions concern your physical function when being active on a higher level. The questions should be answered thinking of what degree of difficulty you have experienced during the **last week** due to your knee.

MOBILIZE CYCLING STUDY

PARTICIPANT ID: _____ **DATE:** _____ (MM/DD/YYYY)

SP1. Squatting

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP2. Running

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP3. Jumping

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP4. Twisting/pivoting on your injured knee

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP5. Kneeling

None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Quality of Life

Q1. How often are you aware of your knee problem?

Never ☐ Monthly ☐ Weekly ☐ Daily ☐ Constantly ☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?

Not at all ☐ Mildly ☐ Moderately ☐ Severely ☐ Totally ☐

Q3. How much are you troubled with lack of confidence in your knee?

Not at all Mildly Moderately Severely Extremely

☐ ☐ ☐ ☐ ☐

Q4. In general, how much difficulty do you have with your knee?

None Mild Moderate Severe Extreme

☐ ☐ ☐ ☐ ☐

Thank you very much for completing all the questions in this questionnaire.

MOBILIZE CYCLING STUDY			
PARTICIPANT ID:		**DATE:**	(MM/DD/YYYY)

Appendix G: Six Minute Walk Test

Allow participant to familiarize themselves with the visual versions of NPRS and BORG scales. Give examples of how to score themselves.

NPRS score BEFORE starting**:**	
BORG score BEFORE starting**:**	

Instructions

"The object of this test is to walk as far as possible for 6 minutes. You will walk in a circle in this hallway for 6 minutes. Six minutes is a long time to walk, so you will be exerting yourself. You will probably get out of breath or become exhausted. You are permitted to slow down, to stop, and to rest as necessary. You may lean against the wall while resting, but resume walking as soon as you are able."

"Remember that the object is to walk AS FAR AS POSSIBLE for 6 minutes, but don't run or jog. Start now, or whenever you are ready."

5 minute remaining: "You are doing well. You have 5 minutes to go."

4 minutes remaining: "Keep up the good work. You have 4 minutes to go."

3 minutes remaining: "You are doing well. You are halfway done."

2 minutes remaining: "Keep up the good work. You have only 2 minutes left."

1 minute remaining: "You are doing well. You have only 1 minute to go."

15 seconds remaining: "In a moment I'm going to tell you to stop. When I do, just stop right where you are."

**If the patient stops walking during the test and needs a rest, do not stop the timer.

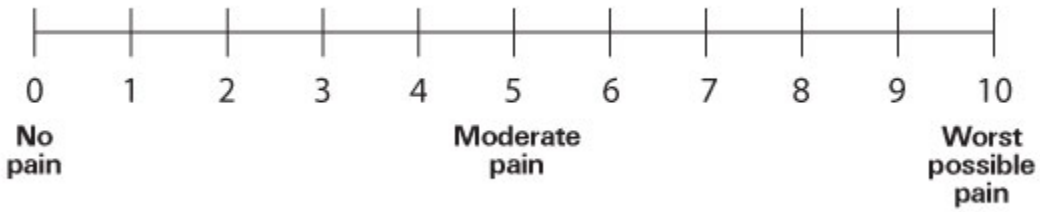
Scoring

NPRS score upon COMPLETION**:**	
BORG score upon COMPLETION**:**	
Distance in METERS covered in 6 minutes:	

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

NPRS (Numerical Pain Rating Scale)



Borg CR10 scale	
Score	**Level of exertion**
0	No exertion at all
0.5	Very, very slight (just noticeable)
1	Very slight
2	Slight
3	Moderate
4	Somewhat severe
5	Severe
6	
7	Very severe
8	
9	Very, very severe (almost maximal)
10	Maximal

Borg's Category Ratio scale taken from Borg, 1982

MOBILIZE CYCLING STUDY

PARTICIPANT ID: _____ **DATE:** _____ (MM/DD/YYYY)

Appendix H: Get Active Questionnaire

CSEP | SCPE THE GOLD STANDARD IN EXERCISE SCIENCE AND PERSONAL TRAINING

Get Active Questionnaire

CANADIAN SOCIETY FOR EXERCISE PHYSIOLOGY – PHYSICAL ACTIVITY TRAINING FOR HEALTH (CSEP-PATH®)

Physical activity improves your physical and mental health. Even small amounts of physical activity are good, and more is better.

For almost everyone, the benefits of physical activity far outweigh any risks. For some individuals, specific advice from a Qualified Exercise Professional (QEP – has post-secondary education in exercise sciences and an advanced certification in the area – see csep.ca/certifications) or health care provider is advisable. **This questionnaire is intended for all ages – to help move you along the path to becoming more physically active.**

☐ I am completing this questionnaire for myself.

☐ I am completing this questionnaire for my child/dependent as parent/guardian.

PREPARE TO BECOME MORE ACTIVE

The following questions will help to ensure that you have a safe physical activity experience. Please answer YES or NO to each question before you become more physically active. If you are unsure about any question, answer YES.

YES	NO	
		1 Have you experienced **ANY** of the following (A to F) **within the past six months**?
○	○	**A** A diagnosis of/treatment for heart disease or stroke, or pain/discomfort/pressure in your chest during activities of daily living or during physical activity?
○	○	**B** A diagnosis of/treatment for high blood pressure (BP), or a resting BP of 160/90 mmHg or higher?
○	○	**C** Dizziness or lightheadedness during physical activity?
○	○	**D** Shortness of breath at rest?
○	○	**E** Loss of consciousness/fainting for any reason?
○	○	**F** Concussion?
○	○	**2** Do you currently have pain or swelling in any part of your body (such as from an injury, acute flare-up of arthritis, or back pain) that affects your ability to be physically active?
○	○	**3** Has a health care provider told you that you should avoid or modify certain types of physical activity?
○	○	**4** Do you have any other medical or physical condition (such as diabetes, cancer, osteoporosis, asthma, spinal cord injury) that may affect your ability to be physically active?

NO to all questions: go to Page 2 – ASSESS YOUR CURRENT PHYSICAL ACTIVITY

YES to any question: go to Reference Document – ADVICE ON WHAT TO DO IF YOU HAVE A YES RESPONSE

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MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Appendix I: Knee and Hip Strength Assessment (Biodex)

Participant's mass (lbs):

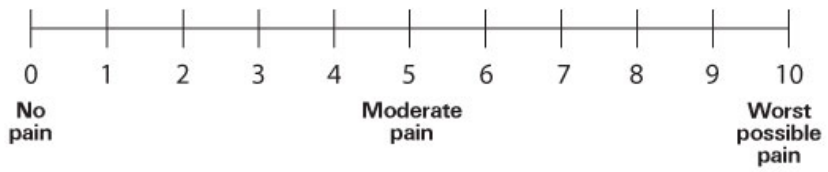
Position and secure participant in Biodex seat. Ensure the axis of rotation of the Biodex arm is aligned with the axis of rotation for knee or hip.

	Left Limb	**Right Limb**
Leg Weight (Hip):		
Lower Leg Weight (Knee):		

MAXIMUM VOLUNTARY ISOMETRIC CONTRACTION

- Set range of motion to avoid full knee extension. NOTE that range of motion limits are denoted "Toward" = Flexion and "Away" = Extension.
- Set reference angle to 90° knee or hip flexion
- When weighing limb, ask participant to fully relax their leg.
- Testing occurs at 60° knee flexion and 60° hip flexion.
- Explain to participants that they should contract as hard as possible and hold for 5 s.
- 8 efforts for each of left and right knee and hip extension. Provide 10 s rest between each effort.
- Provide verbal encouragement.

	LEFT KNEE EXTENSOR	RIGHT KNEE EXTENSOR	LEFT HIP EXTENSOR	RIGHT HIP EXTENSOR
NPRS: (Before 1st MVIC)				
NPRS: (After last MVIC)				



MOBILIZE CYCLING STUDY

PARTICIPANT ID: _____ **DATE:** _____ (MM/DD/YYYY)

Appendix J: Cycling Bouts

Assist participant onto fit-bike after completion of standing, functional left and right knee and functional left and right hips trials. Adjust seat height for 30° minimum left knee flexion when left foot is on pedal positioned at bottom dead center (180°).

- Set trial length to 2 minutes (120 seconds)
- Six total bouts at 60 rpm cadence
  - 20°, 30° and 40° minimum knee flexion
  - 40 W (35W setting) and 75 W workload
- Inform participants when they have 1 minute and 10 seconds remaining
- Provide verbal encouragement
- Set seat height for 30° minimum left knee flexion and gear setting 13 for painful arc trials

	Knee Flexion	Work-load	NPRS Pain L/R		NPRS Comfort	Vertical Seat Pos	Horizontal Seat Pos	Recorded Trial # Opto/Pedal	
Painful Arc Trial 1:	30°	N/A							
1 minute rest, offer longer break									
Bout 1:									
1 minute rest, offer longer break									
Bout 2:									
1 minute rest, offer longer break									
Bout 3:									
1 minute rest, offer longer break									
Bout 4:									
1 minute rest, offer longer break									
Bout 5:									
1 minute rest, offer longer break									
Bout 6:									
1 minute rest, offer longer break									
Painful Arc Trial 2:	30°	N/A							

MOBILIZE CYCLING STUDY

PARTICIPANT ID: _____ **DATE:** _____ (MM/DD/YYYY)

Appendix K: Comorbidity Measure

Instructions

- The following is a list of common problems. Please indicate if you currently have the problem in the first column. If you do not have the problem, skip to the next problem.
- If you do have the problem, please indicate in the second column if you receive medications or some other type of treatment for the problem. Please provide the details of your treatment in the far right columns.
- In the third column, indicate if the problem limits your activities.
- Finally, indicate all medical conditions that are not listed under "other medical problems" at the end of the page.

	Do you have the problem?		**Do you receive treatment for it? (provide details)**		**Does it limit your activities?**		**Treatment details**	
Problem	No (0)	Yes → (1)	No (0)	Yes (1)	No (0)	Yes (1)	List medication(s)	List frequency, dosage & last time taken
Heart disease	N	Y	N	Y	N	Y		
High blood pressure	N	Y	N	Y	N	Y		
Lung disease	N	Y	N	Y	N	Y		
Diabetes	N	Y	N	Y	N	Y		

MOBILIZE CYCLING STUDY

PARTICIPANT ID: | **DATE:** (MM/DD/YYYY)

Ulcer or stomach disease	N	Y	N	Y	N	Y		
Kidney disease	N	Y	N	Y	N	Y		
Liver disease	N	Y	N	Y	N	Y		
Anemia or other blood disease	N	Y	N	Y	N	Y		
Cancer	N	Y	N	Y	N	Y		
Depression	N	Y	N	Y	N	Y		
Osteoarthritis, degenerative arthritis	N	Y	N	Y	N	Y		
Back pain	N	Y	N	Y	N	Y		
Rheumatoid arthritis	N	Y	N	Y	N	Y		
Other medical problems (please write in)								
	N	Y	N	Y	N	Y		
	N	Y	N	Y	N	Y		
	N	Y	N	Y	N	Y		
	N	Y	N	Y	N	Y		

MOBILIZE CYCLING STUDY

PARTICIPANT ID: _____ **DATE:** _____ (MM/DD/YYYY)

COMMON MEDICATIONS

Please complete this section if you take medications that are not listed above

Medications for pain:	(check box)	**List frequency, dosage & last time taken**
Ibuprofen	☐	
Advil	☐	
Aspirin	☐	
Acetaminophen	☐	
Tylenol	☐	
Medications for heart conditions:		
Blood Thinners (eg. Warfarin)	☐	
ACE Inhibitors (eg. Ramipril)	☐	
ARBs (eg. Candesartan)	☐	
Beta Blockers (eg. Metoprolol)	☐	
Calcium Channel Blockers (eg. Amlodipine)	☐	
Cholesterol-lowering agents (eg. Lipitor)	☐	
Water Pills	☐	
Vasodilators (eg. Nitroglycerin)	☐	
Medications for diabetes:		
Metformin	☐	
Glyburide	☐	
Other: (list below)		
	☐	
	☐	

Appendix L: Pilot Data

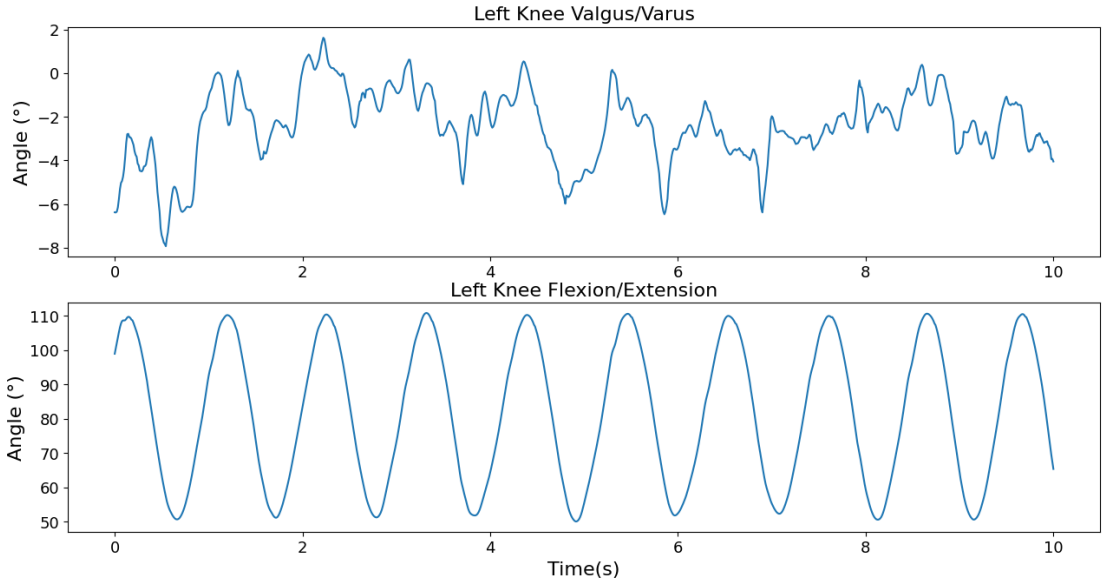


Figure 18 - Knee joint angle pilot data - Filtered at 8Hz cut-off frequency and fourth-order zero lag low-pass Butterworth filter. Flexion and varus are positive.

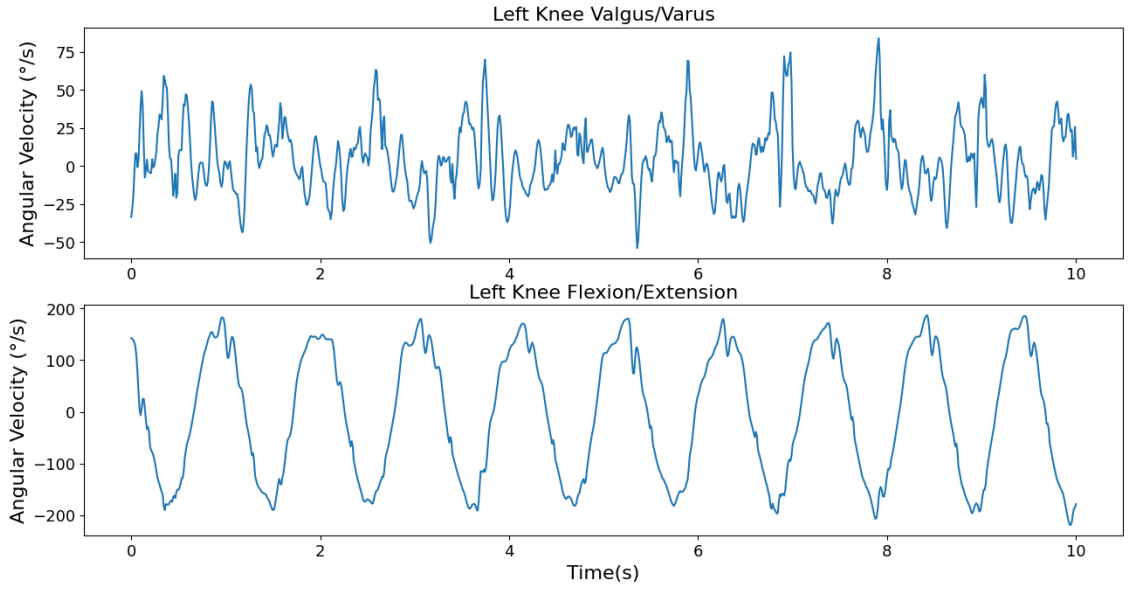


Figure 19 - Knee angular velocity pilot data - Filtered at 8Hz cut-off frequency and fourth-order zero lag low-pass Butterworth filter. Flexion and varus are positive.

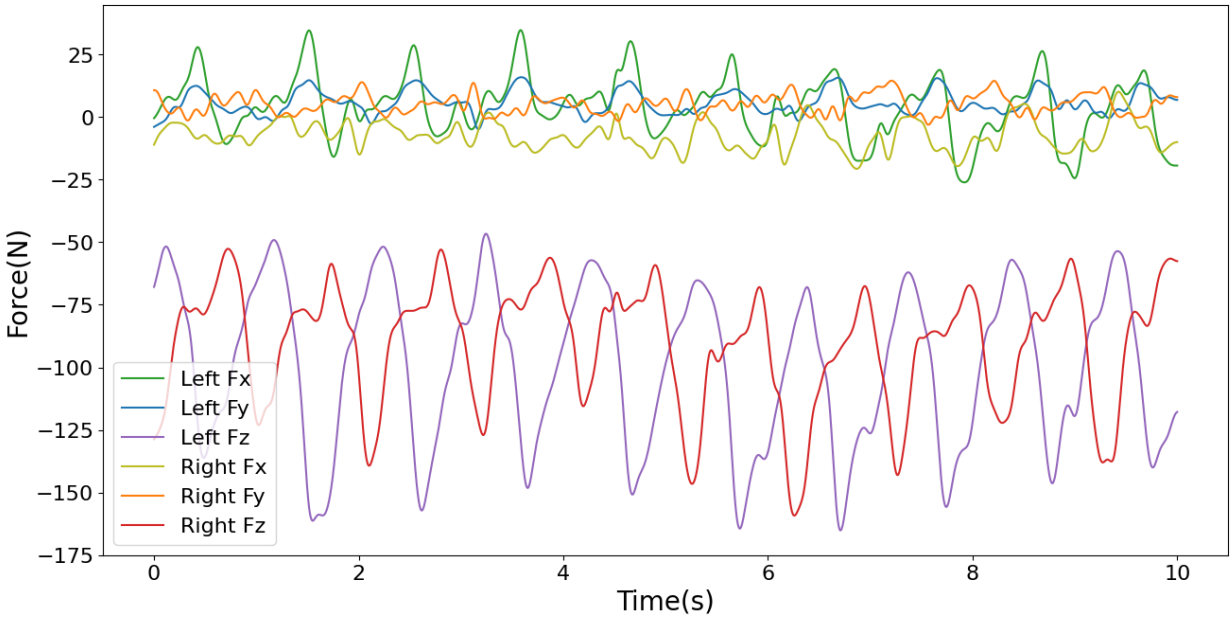


Figure 20 - Force pilot data from instrumented pedals- Filtered at 8Hz cut-off frequency and fourth-order zero lag low-pass Butterworth filter. Fz is the force normal to the pedal surface and a negative value is pressing down on the pedal surface. Fy is the medial/lateral force on the pedal surface where a medial value on the right pedal is positive and lateral force on the left pedal is positive. Fx is the anterior/posterior force on the pedal surface where an anterior value is positive.

Table 9 – Dynamometer pilot data in person with unilateral hip pain – Peaks from top 3 trials from bilateral hip and knee MVIC in extension (participant body mass 68 kg)

Joint	**Left Raw (Nm)**	**Left Normalized (Nm/kg)**	**Right Raw (Nm)**	**Right Normalized (Nm/kg)**
Hip	189.4	2.8	115.4	1.7
Knee	200.5	2.9	193.2	2.8

Appendix M: Participant Data

Table 10 – Participant power (mean) difference, excursion difference and knee pain difference data used in statistical analyses. Difference is dominant side minus non-dominant side.

Bout	Participant	Bilateral Ankle Power Diff (W)	Bilateral Knee Power Diff (W)	Bilateral Hip Power Diff (W)	Bilateral Ankle Excursion Diff (Deg)	Bilateral Knee Excursion Diff (Deg)	Bilateral Hip Excursion Diff (Deg)	Bilateral Knee Pain Diff
20 Deg Knee 40W	P01	-1.32	4.58	-10.40	-3.61	-2.99	-3.59	4
	P02	0.24	-5.30	3.25	0.93	1.25	1.30	2
	P03	-0.32	-7.07	5.00	2.17	-2.65	3.46	0
	P04	-0.44	0.76	-0.24	-1.51	-0.22	1.99	1
	P05	0.58	1.02	-0.94	1.40	0.86	-0.30	0
	P06	-0.56	0.81	-9.22	3.09	-4.62	-1.54	1
	P07	-0.36	-1.51	0.08	5.72	3.22	1.91	0
	P08	-0.36	-0.30	-3.07	0.21	4.50	4.15	2
	P09	0.50	-0.77	3.56	-0.62	0.94	-1.30	0
	P11	-1.09	4.33	-8.29	-0.92	-4.59	-3.29	3
	P12	1.36	1.91	0.89	10.45	3.36	-2.67	0
	P13	-0.71	3.42	-2.08	8.34	1.75	0.28	0
	P14	0.34	2.02	-4.67	4.70	0.37	-4.18	1
	P15	0.03	2.36	0.30	6.73	-2.71	-0.62	0
	P16	5.24	-1.09	9.24	10.27	3.00	-3.69	-2
	P18	1.22	-2.18	6.36	0.43	2.74	-0.90	0
	P19	-0.25	-5.12	6.16	-3.16	-0.79	-0.11	1
	P20	1.15	-5.41	11.41	4.77	-0.03	0.22	1
	P21	2.09	2.77	6.04	4.05	-3.90	-5.14	-1
	P22	0.36	-2.60	6.93	11.41	7.42	2.14	-2
	P23	0.48	-0.02	7.00	-1.21	-1.93	-2.29	0
	P24	0.48	-10.41	6.06	-3.07	0.73	1.17	0
	P25	0.71	-3.93	1.05	4.85	2.49	-0.14	0
	P26	0.23	0.90	1.40	-2.87	-3.82	-0.25	0
	P27	-1.40	-6.46	-1.16	-0.68	1.36	2.66	0
20 Deg Knee 75W	P01	-1.42	7.69	-14.63	-1.61	-1.23	-3.10	4
	P02	0.53	-8.11	7.58	3.05	0.84	0.41	2
	P03	-0.92	-5.77	7.46	-2.81	-2.15	2.17	0
	P04	-1.12	2.88	2.59	-2.30	-2.38	-0.06	2
	P05	-0.32	-0.47	-1.46	-0.06	0.69	0.13	0
	P06	-0.78	3.15	-10.96	3.75	-4.20	-1.26	1
	P07	-0.90	0.11	-3.07	7.40	3.22	1.36	0

	P08	-1.07	1.03	-1.00	-2.46	5.15	5.33	2
	P09	0.95	-1.26	6.63	-0.01	-1.02	-2.33	0
	P11	-1.86	10.59	-11.16	-1.43	-2.95	-1.01	2
	P12	1.26	0.11	-0.90	10.97	4.22	-1.62	0
	P13	-0.79	3.24	-2.91	7.20	1.84	-0.13	0
	P14	0.25	5.14	-7.43	2.15	3.50	-3.22	2
	P15	0.26	6.56	2.51	5.14	-2.11	0.25	0
	P16	7.66	-6.72	16.57	12.50	2.76	-5.76	-2
	P18	1.94	-11.83	12.79	0.82	0.51	-1.32	0
	P19	-0.43	-11.35	12.59	-4.24	-1.77	0.05	2
	P20	0.87	-10.45	17.18	5.08	-1.82	-0.68	1
	P21	2.87	-1.34	10.58	4.26	-3.58	-4.13	-1
	P22	0.91	-2.15	11.41	8.16	7.12	2.47	-2
	P23	0.29	-4.39	8.23	0.22	-0.34	-3.25	0
	P24	0.33	-11.52	12.11	-0.13	1.04	1.20	0
	P25	1.76	-4.69	3.79	2.49	-0.38	-0.76	0
	P26	1.50	-1.48	-0.31	1.22	-4.42	-1.84	0
	P27	-2.72	-9.68	-0.56	1.31	0.60	2.50	0
30 Deg Knee 40W	P02	0.74	-5.69	2.51	-0.06	-0.73	0.85	1
	P03	-0.64	-5.52	4.81	-1.80	-0.93	6.00	0
	P04	-0.50	0.48	1.07	-2.78	-1.47	1.44	1
	P05	0.62	3.37	0.46	-0.93	1.29	-0.05	0
	P06	-1.05	1.89	-8.40	0.23	-5.77	-0.47	1
	P07	-0.36	-0.90	-0.16	6.04	3.26	2.39	0
	P08	-1.05	-2.46	-3.85	-2.72	3.16	3.60	1
	P09	0.46	-3.16	3.80	-1.45	-0.75	-2.09	0
	P10	0.98	-4.09	-2.75	-0.12	6.36	-1.33	0
	P11	-0.43	4.79	-8.63	-0.62	-2.58	-1.57	3
	P12	0.61	-1.91	-0.60	11.57	2.70	-3.84	0
	P13	-0.54	3.60	-1.82	9.89	4.75	1.05	0
	P14	0.50	4.00	-4.76	4.07	4.86	-3.00	1
	P15	-0.21	2.21	-0.59	5.26	-3.82	-2.17	0
	P16	4.58	1.28	10.86	12.19	0.75	-5.62	-2
	P18	0.60	-3.53	10.70	2.66	-0.39	-1.93	0
	P19	-0.42	-4.53	7.14	-2.05	-0.41	0.58	2
	P20	0.82	-8.61	12.56	3.33	0.15	1.24	1
	P21	1.89	3.77	5.62	4.34	-3.18	-4.30	-1
	P22	0.61	-1.73	7.31	8.27	5.53	0.86	-1
	P23	0.05	-1.79	5.79	0.86	-0.07	-2.54	0
	P24	0.36	-3.94	7.67	-2.12	1.35	2.32	0

	P25	1.05	-1.76	2.52	3.46	-2.78	-1.33	0
	P26	0.55	-1.14	0.93	1.87	-3.10	-1.49	0
	P27	-1.07	-3.37	-1.34	0.32	1.00	2.83	0
30 Deg Knee 75W	P01	-1.39	6.63	-12.79	2.97	-1.72	-4.06	3
	P02	1.05	-8.74	7.46	-0.28	0.83	1.35	1
	P03	-0.65	-6.76	5.06	-6.16	-2.61	2.43	0
	P04	-1.02	1.98	3.74	-1.62	-2.99	-0.04	2
	P05	0.62	1.86	-0.34	1.23	0.10	-0.46	0
	P06	-1.39	6.96	-10.17	-2.42	-3.40	0.86	2
	P07	-0.43	0.19	-3.59	7.80	4.05	1.43	0
	P08	-1.10	-0.52	-1.47	-2.74	3.18	3.71	1
	P09	1.10	-1.64	8.92	-2.85	0.67	-1.06	0
	P10	1.16	0.14	-4.33	2.74	3.24	-0.60	0
	P11	-1.03	8.31	-12.87	-0.31	-3.89	-0.43	3
	P12	0.98	4.99	-0.90	7.85	2.12	-2.79	0
	P13	-0.95	4.86	-2.63	5.46	2.49	-0.46	1
	P14	0.43	5.16	-6.94	3.90	3.43	-3.31	1
	P15	0.09	4.87	1.39	3.53	-3.03	-0.53	0
	P16	6.14	-3.83	15.42	11.11	2.08	-5.43	-2
	P18	1.45	-12.60	14.93	2.59	-0.22	-1.92	0
	P19	-0.35	-11.00	10.35	-1.02	-0.48	0.78	2
	P20	0.92	-9.80	15.81	5.28	-1.16	-0.53	1
	P21	3.22	0.50	8.83	5.63	-3.19	-4.65	-1
	P22	1.12	-2.65	12.21	6.47	6.51	1.33	-2
	P23	0.61	-4.78	10.20	1.19	-0.26	-3.25	0
	P24	0.26	-4.91	12.80	-2.09	1.11	1.10	0
	P25	2.18	-2.70	5.56	6.62	-1.92	-1.60	0
	P26	1.43	-2.53	1.69	-0.53	-2.15	-0.25	0
	P27	-2.57	-6.55	-1.94	-2.42	-0.25	3.46	-1
40 Deg Knee 40W	P01	-1.07	4.22	-9.20	-1.78	-1.26	-3.86	2
	P02	0.58	-3.11	4.37	-0.52	0.02	1.92	1
	P03	-0.44	-5.50	3.41	-2.43	-2.38	3.71	0
	P04	-0.63	-3.40	2.15	-2.06	-2.17	2.22	4
	P05	0.04	2.04	-0.24	1.20	1.12	-0.32	0
	P06	-0.29	2.17	-7.09	4.26	-2.71	-2.16	1
	P07	0.29	1.98	-0.79	7.52	5.42	2.59	0
	P08	-1.26	-2.29	-3.77	-2.51	1.33	3.75	1
	P09	0.62	0.77	5.16	-0.50	-1.03	-1.64	0
	P10	0.96	-4.89	-3.27	0.75	2.70	-3.68	0
	P11	-0.33	4.00	-8.54	-1.39	-3.44	-1.84	3

	P12	-0.60	-4.34	-0.66	7.64	0.08	-2.81	0
	P13	-0.41	2.00	-0.87	9.58	1.24	-0.12	0
	P14	0.37	4.68	-5.06	0.82	5.02	-1.35	2
	P15	0.24	0.06	-0.33	4.01	-2.85	-2.17	0
	P16	3.04	-2.00	8.89	11.71	-2.16	-6.20	-2
	P18	0.53	-5.04	7.69	0.25	1.86	-1.19	0
	P19	-0.02	-5.29	7.92	-0.48	-2.95	-0.66	2
	P20	0.71	-5.72	10.82	4.89	1.28	0.91	0
	P21	1.49	1.34	5.84	2.91	-2.76	-5.20	-1
	P22	0.59	-0.61	6.24	7.26	7.22	0.39	-2
	P23	0.13	-1.45	6.10	0.79	-0.54	-3.04	0
	P24	0.51	-2.83	6.96	-1.35	2.92	2.79	0
	P25	0.45	-5.05	2.84	5.92	-4.67	-2.19	0
	P26	0.58	-1.06	1.08	2.00	-2.26	-1.72	0
	P27	-1.06	-5.30	-2.45	0.81	-2.63	-0.13	1
40 Deg Knee 75W	P01	-1.47	6.39	-13.23	1.17	-1.69	-3.21	3
	P02	0.84	-6.37	6.06	-1.01	0.19	1.18	1
	P03	-0.15	-3.53	6.48	-6.96	-3.07	2.11	0
	P04	-1.20	-0.90	3.36	-3.38	-1.85	1.58	3
	P05	0.43	1.09	-0.49	2.58	0.63	-1.13	0
	P06	-0.37	2.23	-9.19	3.19	-3.74	-1.81	2
	P07	0.04	2.04	-2.31	3.82	5.61	3.33	0
	P08	-1.86	-2.06	-3.19	-2.38	0.51	3.73	0
	P09	1.64	-0.39	7.66	1.58	-0.86	-2.06	0
	P11	-0.67	10.73	-10.00	0.60	-2.50	-0.43	4
	P12	1.35	2.91	0.19	9.18	2.63	-2.38	0
	P13	-0.70	2.09	-2.00	6.99	-0.49	-0.92	1
	P14	-0.01	6.79	-7.82	-4.03	3.80	-3.17	2
	P15	0.18	2.53	0.93	3.24	-3.70	-1.62	0
	P16	4.11	-2.51	13.81	11.16	-0.86	-5.65	-2
	P18	0.88	-13.82	16.84	1.18	0.92	-2.01	0
	P19	0.03	-9.54	10.58	1.67	-1.19	-0.39	2
	P20	1.11	-9.98	14.47	7.74	-0.72	-0.30	0
	P21	2.20	0.59	9.18	2.58	-2.55	-5.14	-1
	P22	1.36	-2.07	11.71	7.40	6.15	0.55	-3
	P23	0.99	-5.37	11.76	6.23	-0.87	-4.09	0
	P24	0.35	-4.47	12.47	-1.66	2.73	2.37	0
	P25	0.79	-5.51	4.12	3.75	-2.77	-1.60	0
	P26	1.65	-0.46	1.42	0.94	-1.18	-0.86	0
	P27	-2.66	-6.60	-2.22	-1.29	-3.97	3.28	-1

Table 11 – Participant knee strength difference and hip strength difference data used in statistical analyses. Difference is dominant side minus non-dominant side.

Participant	Knee Strength Diff (Nm/kg)	Hip Strength Diff (Nm/kg)
P01	0.11	-0.43
P02	0.00	0.22
P03	-0.04	-0.22
P04	0.11	0.10
P05	0.31	0.03
P06	0.20	0.47
P07	0.02	0.04
P08	-0.31	0.29
P09	0.42	-0.44
P10	-0.17	-0.04
P11	-0.30	-0.40
P12	-0.37	-0.27
P13	0.21	-0.28
P14	-0.09	0.60
P15	0.44	0.22
P16	-0.08	-0.37
P18	0.17	-0.40
P19	-0.02	0.02
P20	-0.25	0.11
P21	0.68	0.05
P22	0.13	0.03
P23	0.23	0.08
P24	-0.29	-0.17
P25	0.15	0.00
P26	-0.05	0.56
P27	-0.07	-0.41

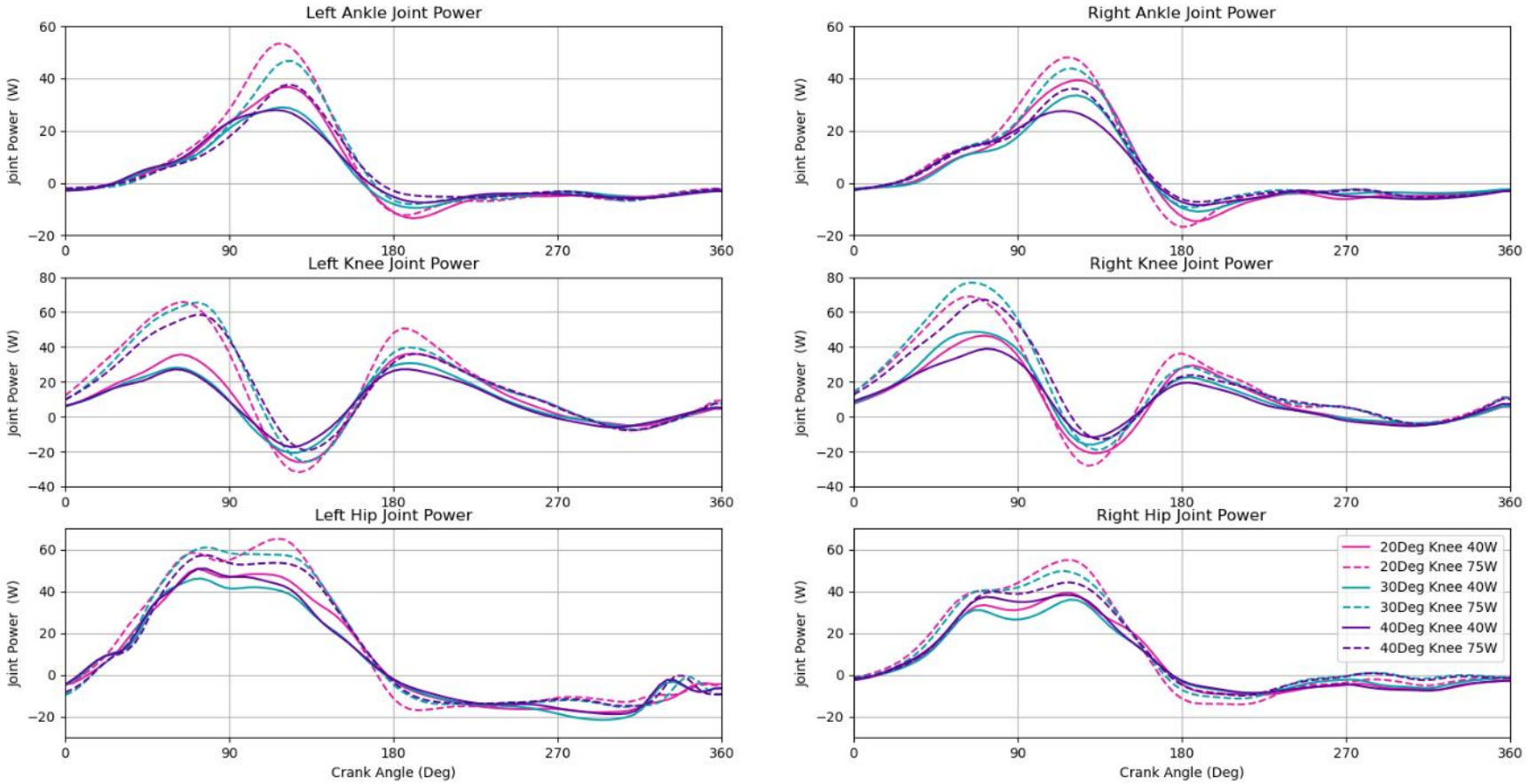


Figure 21 - Joint power plots for participant with no knee pain. This participant was right leg dominant.

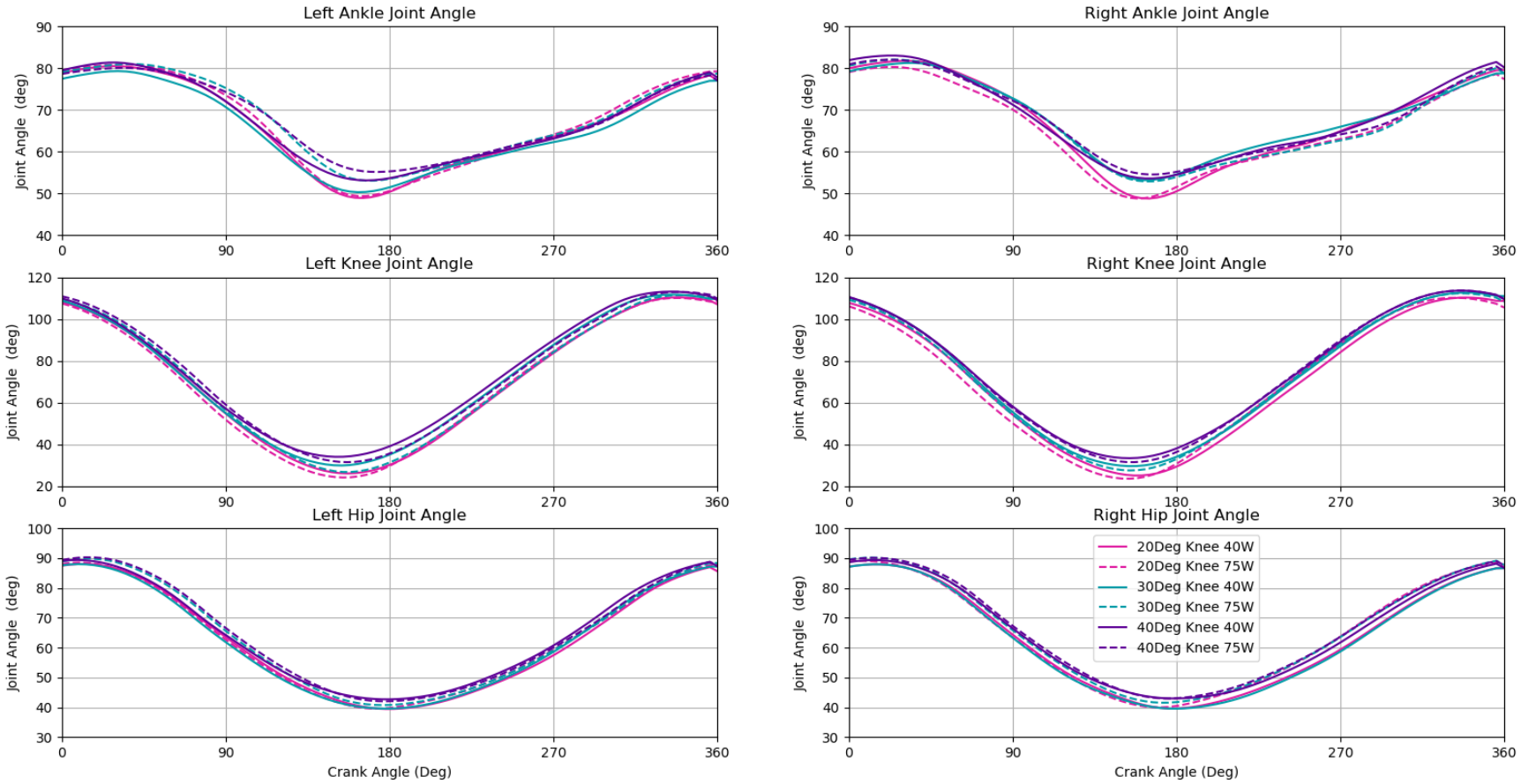


Figure 22 - Joint angle plots for participant with no knee pain. This participant was right leg dominant.

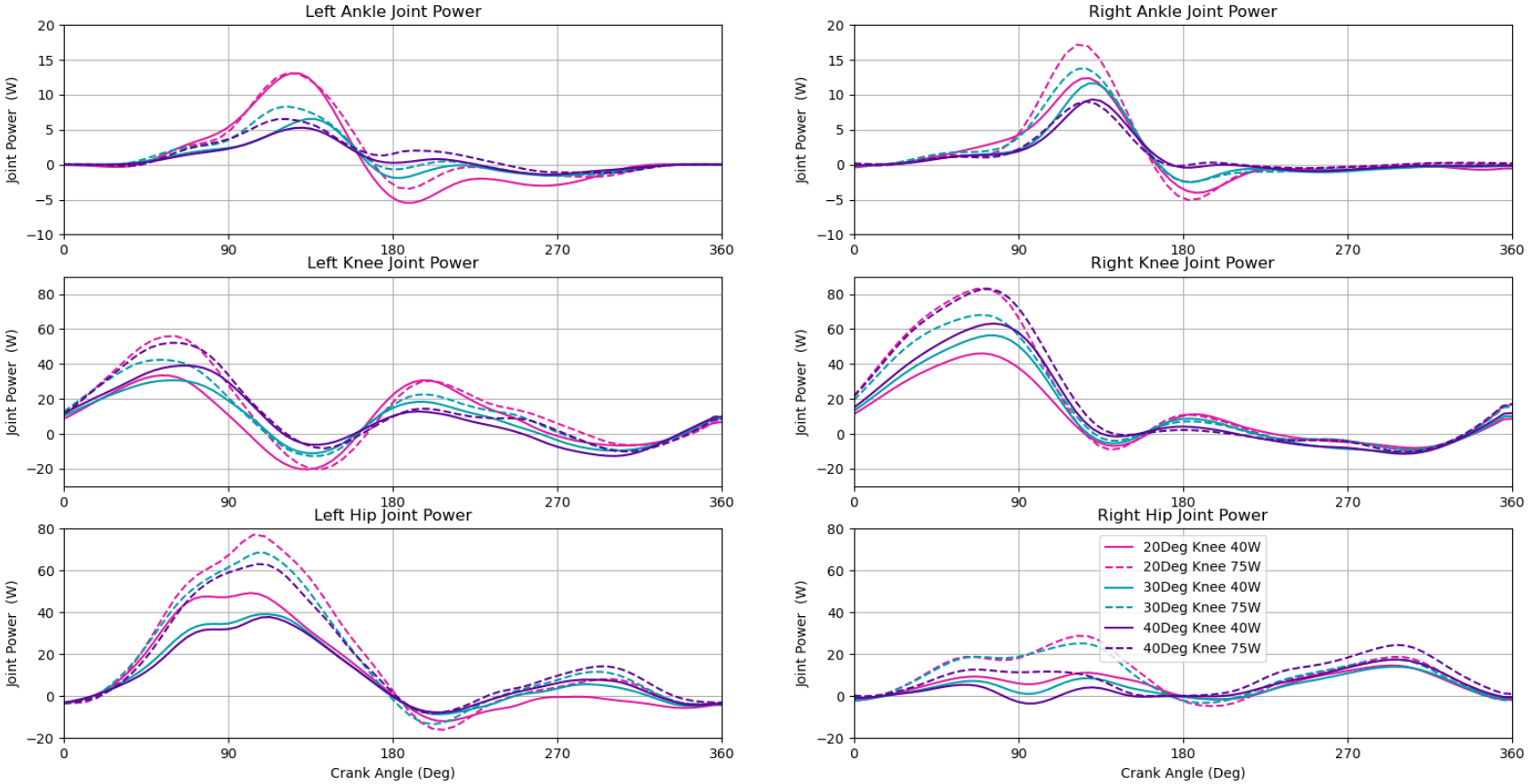


Figure 23 – Joint power plots for participant with a pain difference between knees. This participant was right leg dominant and had unilateral knee pain in their right/dominant knee

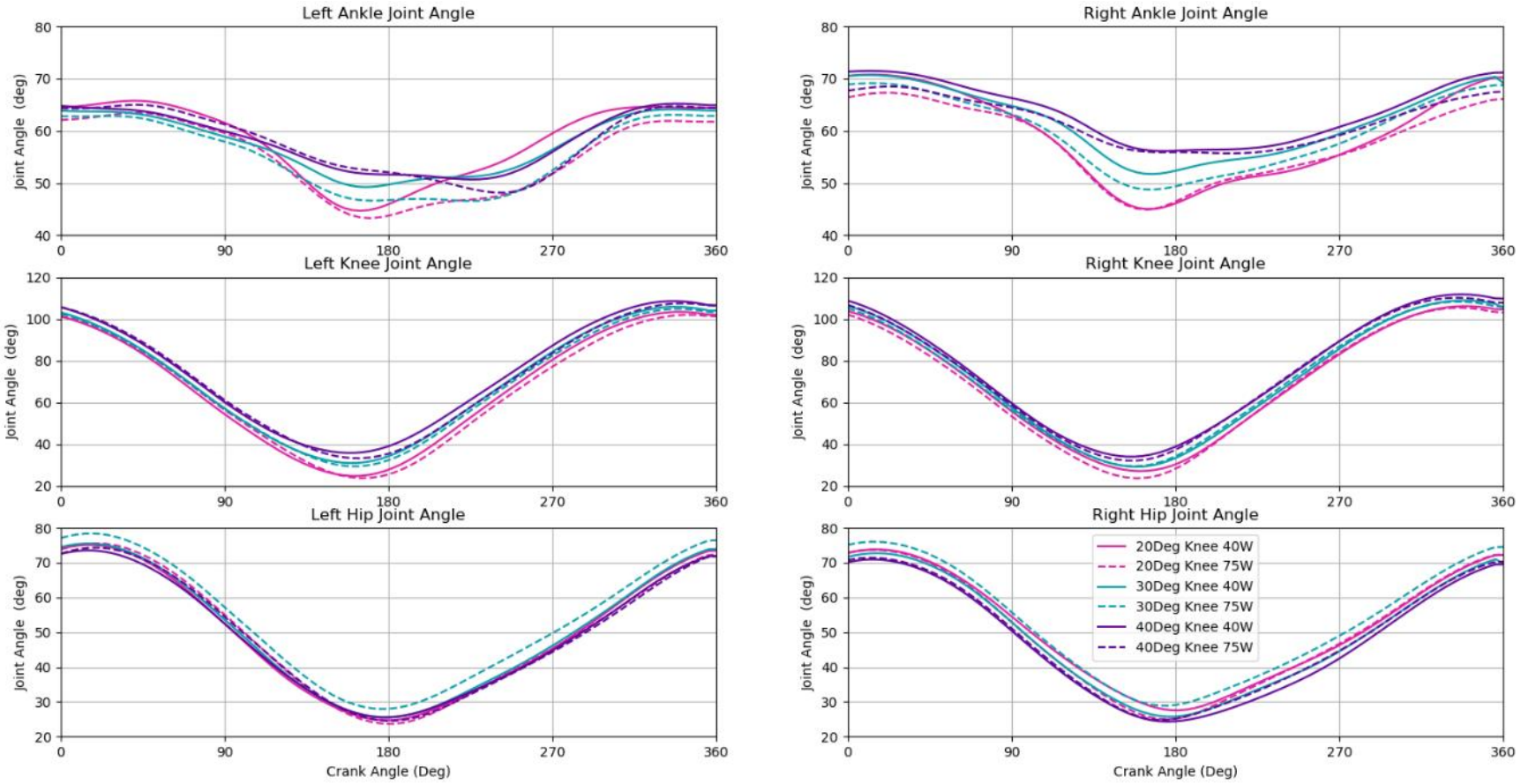


Figure 24 – Joint angle plots for participant with a pain difference between knees. This participant was right leg dominant and had unilateral knee pain in their right/dominant knee