# INVESTIGATING HIGH-RISK BIOMECHANICS IN AGRICULTURAL WORK

By

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# ABSTRACT

**Statement of Purpose:** Osteoarthritis, a debilitating disease resulting in cartilage degradation and loss of mobility, is often instigated by injury or excessive loading of unconditioned articular cartilage. Although agricultural laborers are especially at risk of developing osteoarthritis, quantitative characterizations of occupation-specific activities have not previously been established. Deep flexion movements common to these groups (e.g., squatting or kneeling) may cause excessive contact forces on unconditioned cartilage, potentially initiating osteoarthritis development. Additionally, although cognitive loads can significantly alter gait mechanics, the effects of dual-task conditions (e.g., visual Stroop tests while walking) on contact forces have not previously been established. The purpose of this thesis is to better understand potential factors of osteoarthritis development in agricultural laborers by investigating occupational-specific movement patterns and joint loading during common occupational tasks. **Methods:** The first study evaluated seasonal differences in activity levels for farmers and ranchers by measuring movement intensity via wearable triaxial accelerometers. We hypothesized that ranchers would exhibit consistently high activity levels and that both groups would show an increase in movement intensity in their respective high seasons. The second study sought to establish the effects of cognitive challenges on tibiofemoral contact forces during normal gait and kneel-to-stand transitions in healthy adults. We hypothesized that dual-task conditions would correspond with increased peak tibiofemoral contact forces and that these forces would be positioned farther from the joint center along the mediolateral axis during dual-task conditions. **Results:** The first study findings largely supported the hypothesis: increased movement intensity during high seasons were recorded for both groups, with farmers exhibiting a larger seasonal fluctuation for moderate intensity activities. The second study did not support the hypothesis: cognitive loading did not significantly affect the magnitude of peak contact forces, and peak contact forces occurred closer to the joint center during dual-task conditions than during single-task conditions. However, *post hoc* analysis suggested that other portions of the contact force time series during stance phase were affected by cognitive challenges. **Conclusions:** This thesis provides foundational steps in understanding potential contributing factors of osteoarthritis development in agricultural laborers, directing future investigations towards transitional contact forces in movements simulating livestock handling.

# CHAPTER 1

# INTRODUCTION TO OSTEOARTHRITIS RISK FACTORS IN AGRICULTURAL WORKERS

## Background and Significance of Study

### Risk and Burden of Osteoarthritis in Agricultural Work

Osteoarthritis (OA) is a disease that results in the degradation of articular cartilage, leading to stiffness, pain, and loss of joint function. Total healthcare costs related to the disease annually exceed $89 billion in the United States alone, affecting over 30 million Americans. Several factors are associated with OA development, including increased age, higher body mass index,[1-3] genetics,[4] a history of joint trauma or injury,[5] and occupations involving manual labor or athletics.[6,7] While OA is no longer considered simply a wear-and-tear disease,[8] excessive or vigorous activity appears to increase the likelihood of developing OA.[9,10] Conversely, moderate physical activity is associated with a lower risk of OA development,[9,11] and both obesity and diabetes have been shown to increase the risk of OA.[12,13] Given the complexity of OA risk, careful investigation into the relationship of these factors and OA progression is required in order to reduce its burden on afflicted populations.

The apparently conflicting relationships between physical activity and OA development may be explained by potential for joint injury[7,14,15] and abnormal cyclic joint loading (e.g., squatting, kneeling, and heavy lifting) which can excessively load unconditioned cartilage and initiate OA development.[16-25] For example, athletes who participate in weight-bearing or team sport events that involve aggressive, multidirectional movements are at-risk for OA development because of their propensity for meniscus and anterior cruciate ligament tears.[7] Similarly, a history of manual labor is associated with a higher risk of OA, with this likelihood varying based on the level of mechanization, operation size, and length of time spent in these occupations;[26-27] workers in larger, technologically advanced operations are less likely to suffer OA-inducing injuries or loading cycles than their small-scale counterparts. Whether in

athletics or manual labor, instances of excessive loading or injury help to explain how OA develops in active populations.

Agricultural workers are known to be particularly at risk of lower-body OA development,[28] although the extent of this association varies widely across published studies' specific cohorts. Kirkhorn et al.'s overview of these studies states the odds ratios (OR) of agricultural workers to non-agricultural workers developing OA as OR=1.24, although the studies they cite give odds ratios ranging from OR=1.4 in Finnish farmers to OR=5.2 in dairy farmers.[27] Holmberg et al. found that male farmers with an BMI>26 kg/m2 had an OR=3.1, as opposed to OR=2.8 for non-farmers in the same BMI range and OR=1.4 for lower-weight farmers. Thelin et al.'s investigation on OA in Swedish agricultural workers found that those who worked in animal barns had an OR=1.2 of developing OA compared with non-livestock workers and that dairy farmers in particular had an OR=4.5.[28] The increased odds of OA in livestock handlers may explain the disparity of OA prominence in agricultural workers and highlights the need to differentiate between agricultural groups when discussing OA risk factors.

The presence of OA can be devastating to individual workers and entire operations, especially in small or family operations. Webber et al. found that in small agricultural operations, a ten-point increase in the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)[29,30] score doubled the likelihood of the operation falling into a lower quartile of work capacity and raised the likelihood of self-reporting a lower financial category by nearly a quarter.[31] Of the 299 participants in this study, 22% had been diagnosed with OA and 88% reported joint pain. Limiting this to those with hip and joint pain, the median WOMAC score was 23 and the median age was 62. Because many of these operations depend upon older workers who are the most likely to develop OA, it is imperative that OA risk factors are identified in occupational-specific activities.

The remote location and time-consuming nature of agricultural work makes it difficult to pinpoint the specific risk factors of agricultural workers,[32] although it has been postulated that continual

deep flexion movements[19,22] and working with livestock may be key factors.[33] Separating farmers and ranchers has been suggested as a viable method of subdivision because it assists in isolating the factor of working with livestock from other agricultural tasks.[34,35] This factor is of particular note because of the differences in movements related to occupational demands. For example, ranchers must care for livestock throughout the year while farmers tend to have cyclical fluctuations in physical demand that is tied to growing seasons. Additionally, ranchers perform unanticipated movements in reaction to the animals and are often at high risk of joint injury.[20,21] Characterizing differences between farmers and ranchers regarding physical activity patterns may help understand OA risk factors and is the first knowledge gap that this thesis seeks to address (Chapter 2).

Biomechanical Biomarkers of Osteoarthritis

Articular cartilage is the cartilage that is loaded during normal joint movement and provides a lubricated, protective layer between articulating bones.[36,37] As OA progresses, this articular cartilage erodes and changes the contact interface of the joint.[38] This erosion is driven by multiple processes including cartilage cell metabolic processes and repetitive loading of damaged tissue[7], but of particular interest to this thesis are the biomechanical processes associated with agricultural work. In the knee joint, the medial portion of the articular cartilage typically develops OA before the lateral portion[39], resulting in cartilage and subchondral bone degradation.[4] As the cartilage erodes, the knee often develops a varus deformation[40] (Figure 1.1) and forces in the medial portion of the joint increase until the cartilage fully degrades.[41] With the cartilage no longer lubricating the joint, contact and increased friction between the tibia and femur cause damage to the bone, including lesions and spurs.[42,43] Eventually, OA can result in debilitating pain and loss of joint function that requires a full replacement to remediate.[44] Individuals compensate for this progression or pain and morphological changes through altered movement patterns, which can serve as biomechanical biomarkers of OA.[40] Because these biomarkers are developed in conjunction with result of OA development, their correct characterization

is critical towards understanding OA pathogenesis and has been the primary focus of multiple biomechanical research studies.

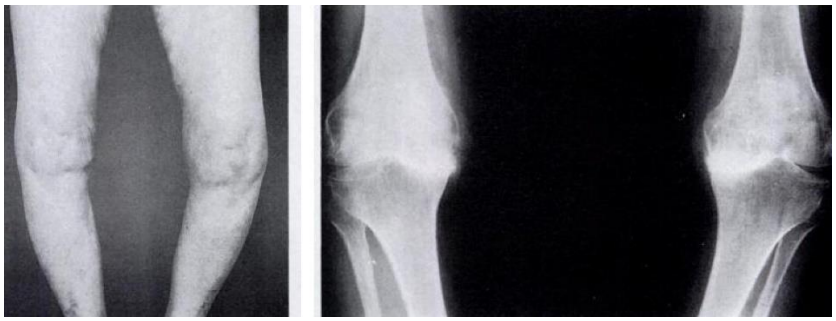

Figure 1.1. Varus Deformation of the Knee. This image from O'Connell[40] et al. depicts varus knee deformation and the corresponding medial osteoarthritis.

Traditionally, biomechanical studies of OA populations have measured kinematic and dynamic variables such as joint angles[46] and moments.[45] These variables can be calculated in a biomechanical lab with motion capture cameras and force plates through inverse kinematics and inverse dynamics. Studies have documented altered kinematics and dynamics associated with different stages of OA in an attempt to relate these variables to OA progression but have been unsuccessful in developing consistent relationships. Using magnetic resonance imaging (MRI) scans to detect cartilage morphology in a 5-year longitudinal study, Chehab et al. demonstrated that reductions in femoral cartilage thickness are associated with decreased knee adduction moments, while tibial cartilage loss is associated with increased knee flexion moments.[47] Their findings agree with those of Edd et al.'s cross-sectional investigation on an asymptomatic population (pre-OA versus healthy controls), which showed an increase in peak knee flexion moments during midstance for those with an increased severity of OA.[48] Several groups have preferred to examine knee adduction moments, although there is disagreement on whether peak or mid-stance adduction moment is more reliable in indicating OA severity.[49-52] Astephen et al. attempted to provide a broader range of kinetics and kinematics across varying degrees of OA.[53]

They found that several biomechanical biomarkers were associated with OA severity, but could not establish which biomarkers and covariates were the most influential in this association. This difficulty is due, in part, to the interconnectedness of these biomechanical biomarkers. Walter et al. investigated the relationship between net moments and medial contact forces in an instrumented knee implant and found that variations in knee adduction moments alone were not adequate to predict changes to medial contact forces.[54] A further complication is that while some biomarkers are measurable prior to the patient feeling pain or discomfort, not all are discernable in the early stages of OA, problematizing their use as a predictor of the disease's progression. Specifically, Edd et al. found no significant differences in knee adduction moments between healthy participants and those with confirmed cases of pre-OA.[48] Because kinematic and dynamic variables have failed to provide a causal relationship of OA progression, there is a need to investigate more fundamental drivers of movement alterations, namely internal joint contact forces.

The kinematics and dynamics typically calculated in OA biomechanical studies are based on ground reaction forces and positional coordinates which can be measured via force plate and motion capture equipment. These measurements are used to measure the net forces and moments for each body segment and do not account for individual contribution of forces such as those due to muscle activation; therefore kinematic and dynamic calculations are limited in their ability to estimate compressive loading of the cartilage (i.e., joint contact forces).[55] The discrepancy between net and contact forces can be demonstrated during normal gait, where the peak axial ground reaction force is typically between 1–1.2 bodyweights (BW).[56] Net loads contribute around 40% to the total contact loads in the knee; the peak force acting on the articular cartilage in the knee (i.e., the contact force) is typically estimated to be 2.5–5 BW (Figure 1.2).[57-59] Contact forces are difficult to measure directly except in instrumented prostheses,[60] which at best provide analogous results to that of natural joints. Instead, the contact forces are often estimated using modern musculoskeletal modeling techniques and optimization

schemes. Despite this added difficulty, contact forces may be better suited to defining causal relationships between OA and movement alterations compared to kinematic and dynamic variables because the contact forces provide more direct measurements of cartilage tissue loading.

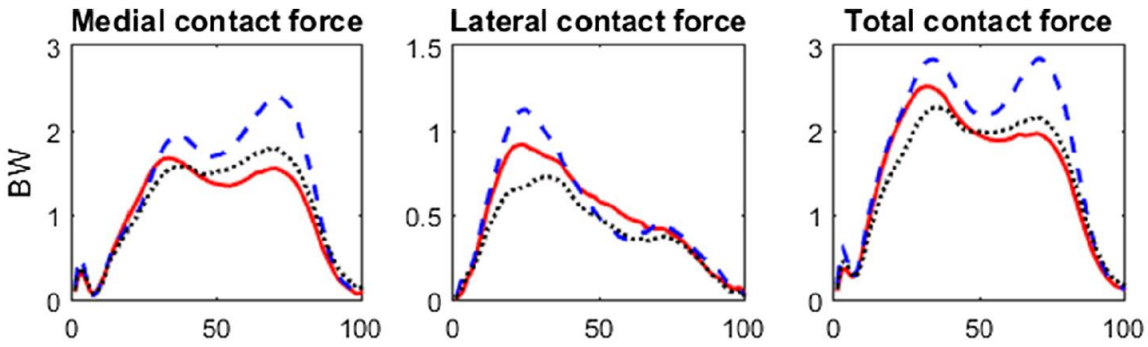


Figure 1.2. Tibiofemoral Contact Forces during Normal Gait. This figure from Zeighami et al.[58] depicts three different models' estimations of tibiofemoral contact forces for normal gait for one stride.

Changes to joint contact forces may be the driving mechanism of the typically studied kinetic and kinematic OA biomarkers. As OA causes articular cartilage to degrade, the contact surface of a joint topologically changes, altering where the contact forces are concentrated in the joint; increases to medial tibiofemoral contact forces are strongly connected with knee OA, with lateral tibiofemoral contact forces sometimes becoming predominant once the cartilage fully degrades.[41,61,62] An investigation into the relationship between joint contact forces, OA severity, and occupational-specific movements of at-risk populations could provide clear insight on the initiation and progression of OA in agricultural workers.

Musculoskeletal Modeling Techniques

Musculoskeletal modeling techniques have been used extensively to study the biomechanics of human movement, often using generic models from motion analysis software packages such as OpenSim[63,64] (Figure 1.3). These models are scaled using a combination of anthropometric measurements and anatomical landmarks (e.g., the femoral epicondyle and anterior superior iliac crest)

that are then tracked using motion capture cameras to provide the kinematic measurements (e.g., knee joint angles).[65,66] Ground reaction force data are typically collected from force plates during the motion capture trials and used in conjunction with the movement data to calculate net forces and moments (e.g., knee adduction moment) for each body segment (e.g., the shank) that satisfy equations of motion. Because soft tissue artifacts can introduce error in the model, both kinematics and dynamics are typically calculated from the ground up (i.e., inverse kinematics and dynamics) to minimize errors in the regions of interest (i.e., lower body segments); any residual error is accounted for in OpenSim by introducing dummy torques at the pelvis. Using residual reduction, the dynamics calculations can be refined by adjusting the kinematics and mass for upper body segments (e.g., the torso) until the dummy loads are reduced. At this stage in the modeling workflow, the biomechanical variables typically analyzed for their relevance to OA (i.e., joint angles and moments) have been calculated. In order to estimate the internal contact loads, sets of linear actuators representing muscle groups are added to the generic model at muscle insertion and origin points. These actuators are scaled with the rest of the model and given constraints according to the model design. Finally, methods such as computed muscle control (CMC), electromyographic-informed CMC, or static optimization use estimate muscle contributions using some optimization scheme, such reducing the sum of squared muscle activations, which in turn can be used to determine joint contact force.

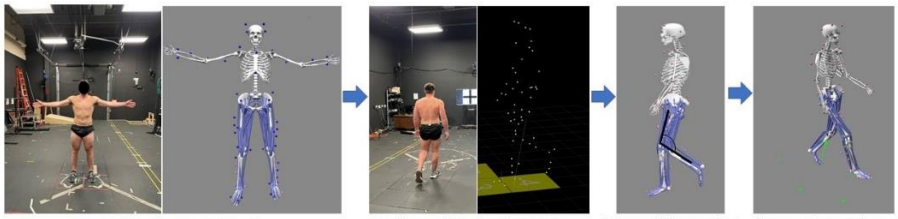


Figure 1.3. Overview of OpenSim Workflow. The static pose informs the model scaling and allows inverse kinematics and inverse dynamics to be solved using the collected tracking marker and force plate data. Once these steps are completed, residual reduction and some method of estimating muscle activations (e.g., static optimization) may be performed.

Musculoskeletal models are typically tailored to specific study aims, with some models designed for specific musculoskeletal disorders[67] and others focused on specialized movements.[68] Movements requiring large flexions in the hip, knee, and ankle joints (i.e., deep flexion movements) have used MRI scans and cadaveric data to accurately scale fiber length, pennation angle, and muscle wrapping around these joints, such as was done in the Rajagopal and Catelli models (Figure 1.4).[69,70] Personalizing models to specific participants can provide details such as displaying dominant limb morphological changes, but the CT or MRI scans required for such resolution is often cost prohibitive.[71-75] Scalable, generic models provide reasonable estimates of internal joint loading, and novel investigations into joint mechanics can use this tool to avoid the time and cost of radiographical scans.[76,77]

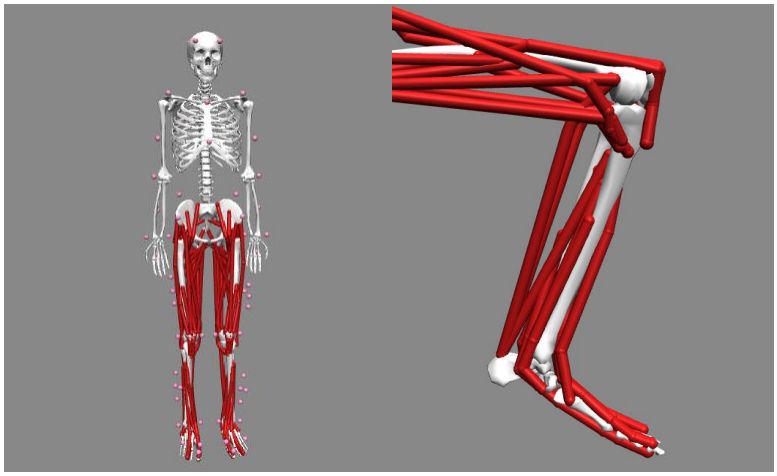

Figure 1.4a-b: Catelli Model. This figure shows the full musculoskeletal model (a) and the parameterized knee joint with linear muscle actuators (b).

Deep Flexion Movements

To understand why agricultural workers have a higher likelihood of developing OA[29], movements specific to their daily tasks must be examined. Due to limitations in laboratory space and equipment setups, rigorous biomechanical data of workplace maneuvers are difficult to collect for farmers and ranchers. It is more feasible for studies to break common maneuvers down into controlled,

repeatable movements easily accomplished in a laboratory space. An approachable first step is to examine deep flexion movements (i.e., movements that require large flexion at lower extremity joints), a category notable both for its frequency in manual labor and its connection to OA development.

Deep flexion movements (Figure 1.5) are often performed while lifting heavy objects, caring for livestock, or repairing equipment, and can generally be categorized as variations of climbing, squatting, and kneeling. Squatting and kneeling can have both immediate and long-term effects on movement mechanics; extended kneeling cycles can temporarily alter gait mechanics, resulting in an abnormal loading on unconditioned joint cartilage.[24] More critically, alterations to tibiofemoral contact forces due to tibial translation and rotation while kneeling can unduly stress the cruciate ligaments and unconditioned cartilage, a known risk factor for OA development.[78,79] However, studies investigating contact forces in deep knee flexion movements are limited.[80,81] Pollard et al. found that compared to bilateral kneeling and squats, single-leg kneeling resulted in the highest peak tibiofemoral contact forces.[82] Van Ginckel et al. performed a survey study in an attempt to associate extended kneeling periods with synovitis but did not collect biomechanical data.[83] Scott et al. performed a more in-depth study on kneeling in OA participants prior to and after total knee arthroplasty that demonstrated that posterolateral cartilage loss significantly affected participants' ability to perform a deep knee flexion prior to surgery.[84] In a study on sit-to-stand transitions, Bouchouras et al. found electromyographic evidence of increased knee muscle co-contraction and hamstring activation in OA participants, resulting in a decreased range of motion in the hips and knees.[85] Similarly, Asay et al. found that OA patients compensated for knee pain while climbing stairs by leaning forward to reduce quadricep demand.[86] Finally, Zhang et al.'s comparison of Beijing and Framingham populations specifically associated prolonged squatting with OA development.[87] While these studies have begun to establish the mechanics and effects of deep-knee flexion movements, they do not provide clear comparisons of tibiofemoral contact loads between movement types. Because tibiofemoral contact forces may be the driving

mechanism behind OA-related movement alterations, it is important to characterize these contact forces in deep flexion movements that could initiate OA.

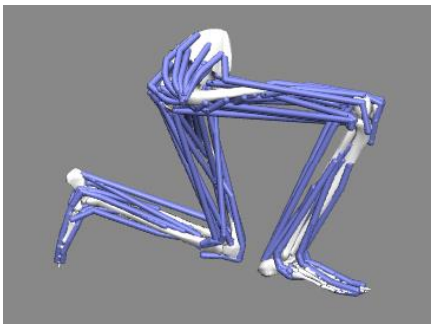

Figure 1.5. Lower Body Musculoskeletal Model of Deep Flexion Movement.

Although kneeling and squatting are not unique to agricultural work, they provide a connection between previously studied movements and activities specific to agricultural work. As the biomechanics of deep flexion movements become better understood, the ability to replicate realistic, agricultural environments in a laboratory setting becomes imperative for correctly understanding risk factors for OA development. One of the key challenges to this process is the difference in a participant's mental focus between normal life and study environments. Cognitive challenges have been used to overcome this incongruity in investigations on kinematic variables, but the effects of cognitive challenge on joint contact forces have not previously been explored.

Cognitive Dual-Tasks

During daily activity, common movements such as walking or sitting are typically performed with little conscience effort. Instead, healthy adults are often mentally preoccupied with an external stimulus or an internal thought. These simultaneous actions (i.e., moving and thinking) are commonly performed examples of multitasking. A person can focus their attention on a movement, such as when navigating an obstacle, and this focus results in altered performance. However, this heightened attention is not

typically maintained for extended periods, especially when performing routine tasks. When study participants are asked to perform some movement in a laboratory setting, their attention is artificially focused on that movement, causing a disparity between the collected data and the daily activity which the study movement is meant to represent.[88]

Movements such as natural gait are not autonomous or reflex reactions; rather, an individual walking naturally depends upon their higher cognitive function to maintain gait stability.[89,90] In particular, executive function is a cognitive domain that is governed by the prefrontal cortex and regulates volition, self-awareness, planning, response inhibition, response monitoring, and multitasking. Each of these subfunctions are believed to impact normal gait components, including path optimization and sensory filtration;[91,92] individuals with impairments to executive function (e.g., dementia and Alzheimer's disease patients) exhibit gait stability loss similar to that of healthy people performing secondary tasks (i.e., dual tasks) while walking.[93,94] This similarity highlights the effects of multitasking on routine movement, whether in a laboratory or a normal environment.

Single-task walking conditions are commonly studied in biomechanical laboratories, such as when participants are asked to "walk normally" while staring at a fixed point across the room. Evidence suggests that such studies do not always accurately represent normal daily movements; rather, daily distractions function as a natural dual task and result in gait instability similar to that of an imposed cognitive challenge.[95,96] Hillel et al. investigated how stride regularity and step length changed between laboratory settings and daily activity and found a disparity in the results between these two environments.[88] This disparity was reduced when the participants were requested to perform a secondary task while walking, indicating that although the dual-task movement quality is often suboptimal when compared to single-task observations, the resulting movements can more closely match those observed during daily activities.

It is possible to mitigate the effects of this hyperfocus on movement (and better reflect real-world scenarios) through the use of cognitively challenging tasks (i.e., dual-task conditions). Cognitive distractions, especially visual distractions,[97] divert participants' attention from the studied movement to complete some mental challenge.[98,99] These cognitive challenges differ depending on the study, but memorization tasks[100] and variations of the Stroop test[101] (Figure 1.6) are common. Memorization tasks require participants to repeat the value, position, or order of colors, letters, or numbers in a briefly shown sequence. Stroop tests require participants to differentiate between congruent and incongruent patterns, such as showing a word that states a color (e.g., green) in a font color that may not match (e.g., blue) and requesting the participant to state the font color.

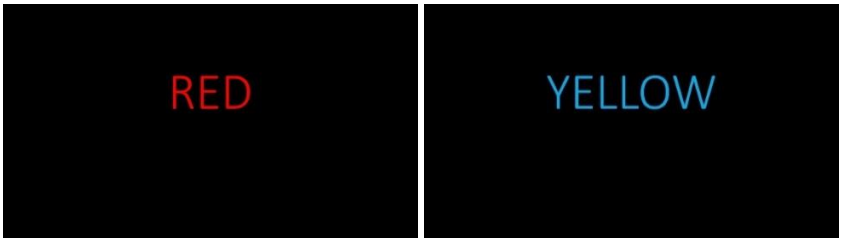


Figure 1.6a-b. Visual Stroop Test. These examples show a congruent (a) and incongruent (b) word and color combination in the visual Stroop test.

For some movements and conditions, the effects of dual-task conditions on human movement are barely discernable, such as during the upper-body lifting studies of Davis et al.,[102] Joseph et al.,[103] and Beach et al.[104] In other studies, however, movements performed in dual-task conditions have resulted in lessened stability, increased postural sway, and decelerated or inconsistent movements.[79] Pellecchia et al. examined the effects of dual-task conditions on postural sway in healthy adults standing on an unstable dense foam platform.[98] In this case, three separate secondary tasks (i.e., the reverse repetition of numbers, addition and classification of numbers, and serial subtraction) were used in a random order in addition to a single-task condition. The study found that as the difficulty of the

secondary task increased, the participants' postural sway increased, meaning that they became less stable. Several other studies have observed cognitive dual tasks having similar adverse effects on movement, including additional investigations on postural sway,[105] jump landings,[106,107] and gait.[108] Although negligible in some scenarios, the effects of cognitive challenges can significantly alter movement mechanics and need to be accounted for when assessing how occupational-specific environments can exacerbate injury risk.

Although cognitive focus can significantly affect movement characteristics, previous studies have not established the effects of dual-task conditions on tibiofemoral contact forces. Filling this gap for both normal gait and deep flexion movements is a fundamental step in understanding potential contributing factors to OA in agricultural laborers and other populations. As a step toward this goal, Chapter 3 presents a study characterizing tibiofemoral contact forces in single- and dual-task conditions of gait and kneel-to-stand.

## Statement of Purpose

Agricultural workers are an essential part of the Montana community and are particularly at risk of developing OA. Due to the time constraints and remote location of this population, however, little investigation has been made into understanding the factors that make its members vulnerable to the disease. Because agricultural work is such a broad category, a simple relationship between this population and OA development is unfeasible, especially given the significant connection between livestock handling and joint injury. Therefore, a quantitative characterization of the activity differences between ranchers and farmers is critical to differentiating OA risk factors between these groups.

Biomechanical laboratories often artificially focus a participant's attention on specific movements, potentially causing a disparity between collected data and routine movement biomechanics. Such variations are critical to address when investigating the risks posed by occupational-specific activities of agricultural workers. Furthermore, while variations to kinetic and kinematic

variables due to OA have been extensively studied, no causal relationship between these variables and OA progression has been developed. Joint contact forces have been associated with OA development and may act as the mechanical drivers for kinetic and kinematic biomarkers of OA. These contact forces have not been well-studied in deep flexion movements, which are both common to agricultural work and associated with OA-development. Where these joint contact forces have been studied, no investigation has been made into the effects of cognitive challenge on these forces. This presents a clear knowledge gap that must be filled before an accurate, causal relationship between OA development and movement alterations can be developed.

The purpose of this study is to provide insight regarding which factors should be considered in developing a relationship between agricultural work and OA initiation (Figure 1.7). In order to accomplish this task, the following questions were asked: 1) What activities patterns characterize the distinction between farming and ranching work? 2) What are the characteristic knee joint mechanics in movements common to agricultural work? To address these questions, Chapter 2 of this thesis characterizes agricultural workers' work-related movements using tri-axial accelerometers and work logs during their low and high work seasons. Chapter 3 presents a detailed biomechanical investigation into the effects of cognitive challenges on tibiofemoral contact forces during normal gait and kneel-to-stand transitions in healthy, active adults. Finally, Chapter 4 provides a concluding discussion relating the findings of these two studies, as well as suggestions on the direction of future investigations.

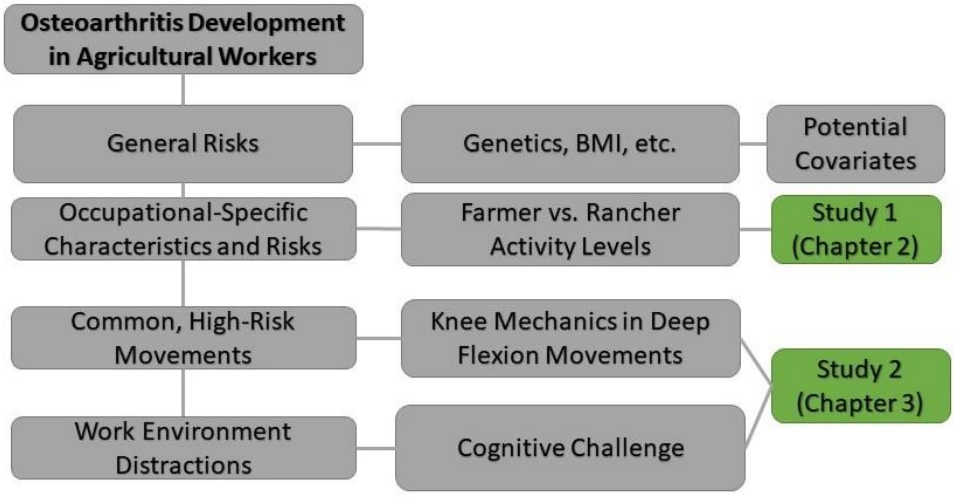


Figure 1.7. Thesis Flowchart. This chart provides a broad overview of the relationship between key aspects of both scientific chapters within this study.

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# CHAPTER 2

# SEASONAL FLUCTUATIONS IN MOVEMENT INTENSITY BETWEEN FARMERS AND RANCHERS

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# SEASONAL FLUCTUATIONS IN MOVEMENT INTENSITY BETWEEN FARMERS AND RANCHERS


## Abstract

**Objective:** Agricultural workers have an increased risk for osteoarthritis, but risk factors unique to agricultural occupations have not been fully explored. One previously established osteoarthritis risk factor is increased time working with animals, motivating the need to understand the differences in physical demands between those who work with animals (i.e., ranchers) and those who work exclusively with crops (i.e., farmers). This study evaluated the physical activity of farmers and ranchers, investigating how seasonal work fluctuations influence their activity patterns. We hypothesized that high seasons would coincide with increased MI, and that ranchers would average higher MI than farmers year-round. **Methods:** Activity logs and accelerometer data were collected from 18 farmers and 24 ranchers (48 ± 15 years; 1.8 ± 0.1 m; 86 ± 19 kg) during three-day periods within participants' self-proclaimed high- and low-demand work seasons. Accelerometer data were used to define movement intensity (MI) for activity level characterization. **Results:** Linear mixed-effects models (fixed factors: Group, Season, and Group*Season) showed increased average MI during high seasons (Season $p = 0.001$), and greater seasonal fluctuations in the percent of time spent performing moderate intensity activities for farmers (Group*Season $p = 0.034$). The MI data indicate that ranchers remain more active than farmers during winter. The activity logs showed the ranchers consistently dealing with cattle year-round, while the farmers emphasized personal needs and equipment maintenance during winter. **Conclusion:** These findings support the argument that ranching-specific occupational demands require sustained moderate physical activity year-round, justifying further investigation into the role of these occupational demands in osteoarthritis risk.

## Introduction

Osteoarthritis (OA) is a debilitating disease that affects 30 million Americans and results in over $89 billion in annual healthcare costs (1). OA can develop in the upper or lower body, with the hip, knee, and ankle joints being commonly affected areas (2). As the disease develops and cartilage degrades, the area can become inflamed and bone lesions can develop (3, 4). The resulting pain and stiffness can limit mobility and physical activity, which can lead to deconditioning and the development of obesity (5). Advanced cases of OA often require total joint replacement surgery to alleviate symptoms and restore mobility (6).

Several factors are known to heavily influence the development and location of OA, including body mass index (BMI) (7-9), genetics (10), age (11), injury (12), and occupation (13). Obesity and diabetes have both been shown to increase the risk of OA (14, 15), whereas moderate physical activity has been associated with a lower risk of OA (16, 17), negating the idea of OA as simply a wear-and-tear disease (18). Studies have found, however, that excessive or vigorous activity may increase the likelihood of developing OA (17, 19), and a history of heavy manual labor can have similar effects (20). Agricultural workers in particular have been flagged as an at-risk group for OA, with studies showing that these workers have an increased likelihood of developing OA the longer they remain in their profession (21), although this likelihood can vary with operation size and mechanization (22, 23).

Several studies have investigated the tendency of agricultural workers to develop OA, but the mechanisms driving this tendency are not fully understood. Prolonged exposure to mechanical vibrations, such as extended shifts working on a tractor, was once considered a risk factor, but this explanation has since been determined to be inadequate (24). A history of joint injury has been shown to be a significant risk factor in OA development (25, 26), and one study classifies past joint injury as the primary indicator of OA development in agricultural workers (27). However, the unreliability of injury statistics in this population can make joint injuries difficult to track (28). Other researchers consider

abnormal cyclic loading, such as the squatting or heavy lifting inherent to agricultural work, to be the predominant risk factor (29-31). Because no single or consistent explanation of the connection between OA and agricultural workers at large exists, some studies break this population into subgroups, such as farmers and ranchers (32, 33). This approach accounts for major differences in work activities and provides a more focused approach to understanding OA risk factors in agricultural workers.

Within these subgroups, ranchers—those who work primarily with livestock—may be at higher risk for OA development than farmers, whose work primarily deals with crops (34). One plausible factor is ranchers' high potential for excessive impact forces in their daily tasks. As they deal with large animals whose behavior can be unpredictable, ranchers are commonly required to react to the animals' movements, which may increase the risk of injury and/or joint loading (35, 36). Additionally, activities such as cleaning stalls and milking force ranchers into awkward physical positions, such as squatting and bending over, which provides a second plausible explanation for their increased risk of OA development (37, 38).

Research into the causes of OA proclivity in agricultural workers lacks a thorough understanding of how farmers' and ranchers' physical activity levels differ or how their work patterns are affected by seasonal fluctuations and physiological factors. Therefore, the purpose of this study was to investigate the differences in physical activity patterns between ranchers and farmers by studying the activity levels of both groups in their self-proclaimed high- and low-demand seasons. We hypothesized that ranchers would show a high activity level throughout the year and that both ranchers and farmers would show an increase in movement intensity (MI) in their respective high seasons.

## Methods

To be eligible for this study, participants were required to be 18–85 years old and own, manage, or work on a farm or ranch year-round with at least 50% of their work-related activities being affiliated

with the farm or ranch, and have manual labor as a normal part of these work-related activities. Ranchers were defined as those who manage livestock, working with or tending to animals at least 5 hours in a typical workday. Farmers were defined as those who grow crops and do not tend to livestock for at least 5 hours in a typical workday. Data were collected remotely from participants during two 3-day periods, with one period occurring during the high-demand season and the other occurring during the low-demand season. The high and low seasons for farmers and ranchers were self-reported on participant screening questionnaires.

For each data collection period, participants wore an inertial measurement device to quantify physical activity patterns. DynaPort MoveMonitor+ sensors (McRoberts B.V; Netherlands) were continuously worn by each participant for three days during both the high and low season, aside from when the participants were sleeping or showering. All the participants were provided with detailed directions, brochures, and sensor placement training prior to the data collection. The sensors were worn on the lower back underneath normal clothing to approximate the participants' centers of mass and recorded triaxial (vertical, mediolateral, and anterior-posterior) linear accelerations and angular velocities at 100 Hz. The data were processed in MATLAB (MathWorks, Natick, MA), and, following the methods presented by Van Hees et al. (39), bandpass filtered using a 4th order Butterworth filter with 0.2–10 Hz cutoff frequencies. The square root of the summed, squared values of the triaxial accelerations averaged over 1-second intervals were used to calculate MI at any given time throughout the entirety of each 3-day data collections. MI served as the primary dependent variable for this study and was selected based on prior correlation between MI and metabolic expenditure in a different population. (39) The activity levels were binned as sedentary, light, moderate, or vigorous based on the associated MI. The MI thresholds for these activity categories were defined according to a pilot study (Table 2.1; Supplemental Tables 2.1a–b) and corroborated with previous study findings (40). For the purpose of the current study, focus was directed at the categories of moderate activity (activities similar

to a brisk walk) and vigorous activity (activities similar to running). In addition to the numerical value of MI, the percentage of time spent in moderate or vigorous activity was also calculated.

For each data collection period, the participants were asked to complete the Knee Injury and Osteoarthritis Outcome Score (KOOS) survey (41). Following published guidelines, the survey was scored from 0–100 for each category, with 0 representing the poorest outcome (42). Additionally, the participants completed activity logs, in which they recorded the types of work they performed for each day of the 3-day period and the approximate duration of each task. The logs were formatted as free response to allow the participants to best elucidate their individual tasks. Responses were sorted by group and season and then categorized based on similarities for subsequent qualitative analysis. In cases where more than one category was applicable, the log entry was placed only into the best fitting category to avoid double counting entries.

Linear mixed-effects models were used to test our hypotheses. The models included fixed factors of Group, Season, and Group*Season. Participants were set as random factors in the model, and covariates of age, sex, and BMI were considered. The primary dependent variable was the average MI during active hours (i.e., omitting periods when the sensor was not worn). Additional exploratory analyses were performed for the dependent variables of active minutes spent in moderate activity, active minutes spent in vigorous activity, percentage of active time performing moderate intensity tasks, and percentage of time performing vigorous intensity tasks. The dependent variables were transformed via natural logarithm when necessary to obtain normally distributed model residuals. Model coefficients were standardized by subtracting the variable mean and dividing by the standard deviation (43). The relative fit of each model was compared through adjusted R2, AICc, and BIC values to determine which covariates should be included (44, 45). Finally, an additional set of mixed-effects models were created for the dependent variables of the KOOS outcome scores for pain, symptoms, activity in daily living (ADL), sports and recreation, and quality of life (QOL).

| Category | Sample Activities | MI Threshold (g) |
|---|---|---|
| Sedentary | Sitting or lying down | 0–0.128 |
| Light | Walking comfortably | 0.129–0.445 |
| Moderate | Walking briskly | 0.446–0.858 |
| Vigorous | Running | >0.858 |

Table 2.1. Movement Intensity (MI) Level Thresholds and Descriptions.

## Results

Forty-two Montana agricultural workers provided an Institutional Review Board (IRB)-approved informed consent to participate in the study. This group was comprised of 18 farmers (age: 45 ± 15 years; height: 1.8 ± 0.1 m; weight: 80 ± 17 kg) and 24 ranchers (age: 51 ± 14 years; height: 1.8 ± 0.1 m; weight: 91 ± 20 kg) (Table 2.2). Seventeen of the farmers and twenty-one of the ranchers completed the study in both the high and low seasons. Four participants only provided data in the high season and six of the ranchers did not provide complete detailed demographic information.

After controlling for the covariates of age, sex, and BMI, the results of the mixed-effects models for the MI dependent variables demonstrated consistent effects of Season with isolated Group effects (Table 2.3). The first of these models showed that the average MI of total active time in the low season (Figure 2.1) was 0.083 times the acceleration of gravity (g) with a standard error (SE) of 1.036 g; in the high season, the average MI was 0.096 g (SE = 1.035 g). In this analysis, Season was a significant factor ($p = 0.001$), but neither Group nor Group*Season were significant. Age ($p < 0.001$) and BMI ($p = 0.004$) both proved significant covariates for this analysis. Using the percentage of active time spent in moderate activity as the dependent variable (Figure 2.2) revealed that, during the high season, the farmers spent 0.60% (SE = 1.19%) of their active time in moderate activity versus 0.55% (SE = 1.21%) for the ranchers.

| Demographic | Farmers | | Ranchers | |
|---|---|---|---|---|
| | Range | Count | Range | Count |
| Age (Years) | Not given | 0 | Not given | 6 |
| | 45 ± 15 | 18 | 51 ± 14 | 18 |
| Mass (kg) | Not given | 0 | Not given | 5 |
| | 80 ± 17 | 18 | 91 ± 20 | 19 |
| Height (m) | Not given | 0 | Not given | 5 |
| | 1.8 ± 0.1 | 18 | 1.8 ± 0.1 | 19 |
| Sex | Not given | 0 | Not given | 4 |
| | Male | 12 | Male | 16 |
| | Female | 6 | Female | 4 |
| Operation Size* | Not given | 0 | Not given | 5 |
| | 1–10 | 7 | 60–200 | 5 |
| | 90–1,000 | 5 | 250–950 | 10 |
| | 1,500–5,000 | 6 | 1,400–2,000 | 4 |
| Continuous variables presented as mean ± standard deviation<br>*Farm: acres; ranch: heads of cattle | | | | |

Table 2.2. Demographics for Farmers and Ranchers.

| Model Dependent Variables | Coefficients for Fixed Factors | | | Standardized Coefficients for Covariates | | |
|---|---|---|---|---|---|---|
| Dependent Variables | Group | Season | Group*Season | Age | BMI | Sex |
| Average MI of Active Hours | -0.037 | 0.073*** | 0.025 | -0.114*** | -0.106*** | - |
| Active Minutes in Moderate MI | -0.103 | 0.272*** | 0.102* | -0.648*** | -0.328** | - |
| Active Minutes Vigorous MI | -0.208 | 0.148 | -0.016 | -0.824*** | -0.290 | 0.332 |
| % Active Time— Moderate MI | -0.075 | 0.207*** | 0.115** | -0.67*** | -0.195 | - |
| % Active Time— Vigorous MI | -0.181 | 0.084 | -0.002 | -0.843*** | -0.156 | 0.331 |
| * p<0.050<br>** p<0.010<br>*** p<0.001 | | | | | | |

Table 2.3. Model Outcomes for Occupational and Physiological Factors for MI Characterization

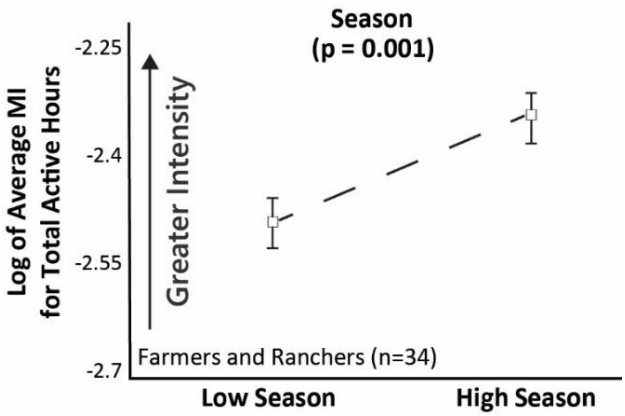


Figure 2.1. Seasonal Average for Movement Intensity of Active Hours for Farmers and Ranchers Combined. Data points and error bars correspond to linear mixed-effects model estimates of means and standard errors, respectively.

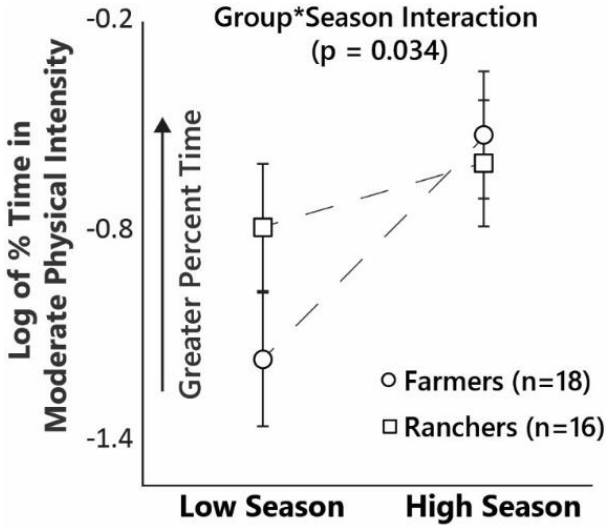


Figure 2.2. Group-by-Season Interaction with Standard Error for the Percentage of Time in Moderate Intensity. Data points and error bars correspond to linear mixed-effects model estimates of means and standard errors, respectively.

The farmers spent 0.31% (SE = 1.20%) of the low-season active time in moderate activity, whereas the ranchers maintained moderate activity for 0.46% (SE = 1.21%) of their low-season active time. The fixed factors Group*Season ($p = 0.034$) and Season ($p < 0.001$) proved significant with this dependent variable, as did the covariates of BMI ($p = 0.032$) and age ($p = 0.001$), with greater BMI and

age associated with less activity. Finally, an analysis of the percentage of time spent in vigorous activity did not show the Season, Group, or Group*Season to be significant, although age ($p < 0.001$) was significant, and sex ($p = 0.056$) approached significance.

According to the questionnaires completed during the participant screening, the ranchers considered their high season to be calving and branding seasons, while the farmers considered sowing time their high season. Both the farmers and ranchers identified winter as their low-activity season. Figure 2.3 presents counts of the farmers' and ranchers' activity log responses for both the high and low seasons. During the high season, the ranchers recorded passive cattle work (e.g., checking on, feeding, or unspecified work with cattle) 203 times (59% of the total recorded entries in the ranchers' high season logs), and active cattle work (e.g., veterinary services, moving, milking, and tagging) 39 times (11%). During the low season, the responses were reduced to 103 passive cattle logs (41% of the total recorded entries in the ranchers' low season logs) and 8 active cattle logs (3%). Following cattle work, the ranchers recorded chores (e.g., yard work, unspecified chores, and firewood) most frequently. Additional categories included personal needs (e.g., meals and showers), maintenance and repair (e.g., pastures, mechanics, and irrigation), administration (e.g., phone calls, paperwork, and office work), vehicle use, non-cattle animal (e.g., sheep and pets), and non-agricultural (e.g., volunteer work and workouts).

The farmers only recorded in total 1 instance of animal work of any kind in the high season and 3 instances in the low season. The most frequently recorded high-season category was irrigation work (e.g., pipes, irrigation, and changing water), which occurred 40 times (29% of the total recorded entries in the farmers' high season logs); there were no records of irrigation work during the low season. The next most common activities were fieldwork (e.g., planting, seeding, weeding, field preparation, harvesting, and non-specified farm work) and chores. Additional categories included personal needs, vehicle use, maintenance and repair, and administration.

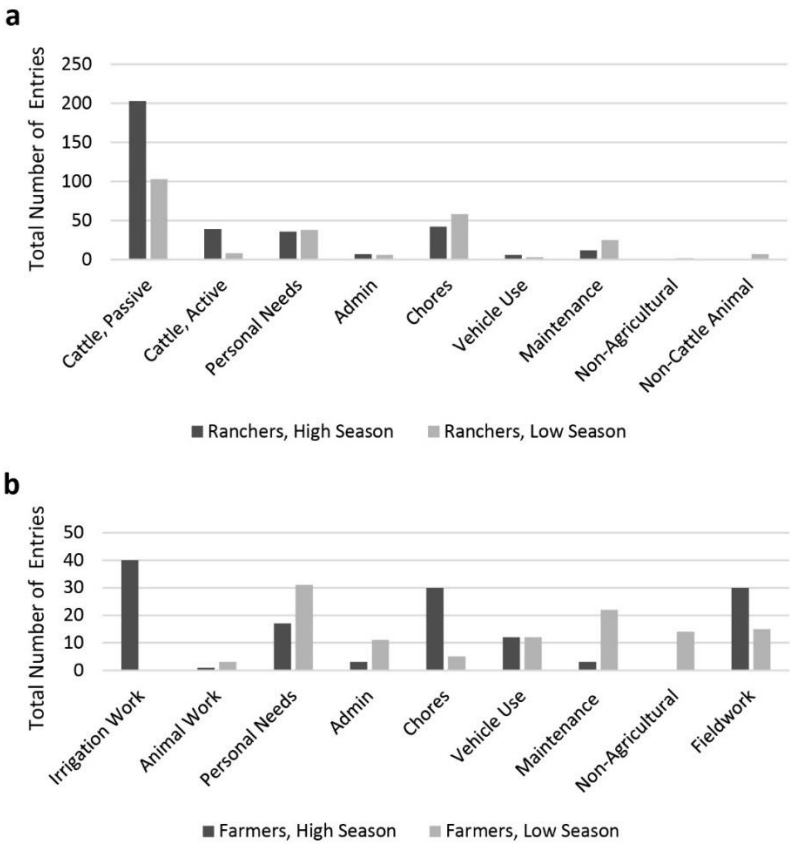


Figure 2.3a-b. Activity Logs by Season for (a) Ranchers and (b) Farmers.

The mixed-effects models comparing the KOOS scores to the same fixed factors and covariates (Table 2.4) indicated no significant relationship between the KOOS categories of symptoms, ADL, sports and recreation, or QOL and any fixed factors or covariates. With KOOS pain as the dependent variable (Supplemental Figure 2.1), the fixed factor Group*Season ($p = 0.050$) was trending towards significance, but no other fixed factors or covariates were significant. Within this analysis, the ranchers reported higher pain levels than the farmers in both seasons. However, a post-hoc Tukey analyses with a 95% confidence interval failed to show significance between the pairwise comparisons. During the high season, ranchers' KOOS pain score averaged 78 (SE = 4.7), with 100 signifying no pain. In the low season, their pain decreased to an average of 80 (SE = 4.6). The farmers' averaged score during the high season was 92 (SE = 4.8); their reported pain levels increased during the low season, averaging 89 (SE = 4.8).

Finally, a post-hoc analysis comparing the percentage of time spend in moderate MI to the KOOS pain scores showed no significant relationship between them.

| Model Dependent Variables | Coefficients for Fixed Factors | | | Standardized Coefficients for Covariates | | |
|---|---|---|---|---|---|---|
| | Group | Season | Group*Season | Age | BMI | Sex |
| KOOS Pain | 5.603 | 0.402 | 1.196* | - | - | 1.631 |
| KOOS Symptoms | 4.591 | 0.459 | 1.304 | - | - | 2.918 |
| KOOS ADL | 4.891 | 0.003 | 0.043 | - | - | 0.879 |
| KOOS Sports/Recreation | 6.368 | 0.242 | 1.751 | - | - | 1.055 |
| KOOS QOL | 6.746 | 1.389 | 1.589 | - | - | 2.200 |
| * p<0.050 | | | | | | |

Table 2.4. Model Outcomes for Occupational and Physiological Factors for KOOS Scores.

## Discussion

The purpose of this study was to investigate the effects of seasonal work fluctuations on physical activity in farmers and ranchers to provide a foundation for exploring why ranchers appear to have a higher susceptibility to developing OA than farmers. We hypothesized that the ranchers would exhibit a high activity level throughout the year and that both the ranchers' and farmers' MI would increase in their respective high seasons. These hypotheses were largely supported by the study's findings: while both groups showed signs of elevated intensity of physical activity during their respective high seasons, the farmers showed a marked reduction in activity during the winter, and the ranchers maintained moderate activity throughout the year.

For the primary analyses, the average MI for all active hours was found to not significantly explain Group and Group*Season. Independently, however, Season was a significant fixed factor for the average MI, showing increased activity for both groups in their self-proclaimed high seasons. The lack of

significance does not necessitate that farmers and ranchers have the same likelihood of OA development but only indicates that both farmers and ranchers work more intensely during their high seasons. Moderate activity comprised less than 2% of their active time for either season, which is less time than older runners commonly train (46). The agricultural workers' relatively low percentage of time spent in moderate activity supports the idea that any increased tendency towards OA for farmers and ranchers is most likely not related to simple wear and tear from daily activity, and that specific instances of excessive joint loading from agriculturally-unique tasks may be more likely to be associated with any OA proclivity.

The fact that the majority of movements in both seasons were categorized as either light or sedentary may contribute to why the average MI of active time remained similar in both seasons. Examining the percentage of time spent in moderate MI provided a clearer picture of how the ranchers and farmers differed in their vocation-specific activity levels. The analyses of the percentage of active time spent in moderate MI as the dependent variable showed that the ranchers maintained a similar percentage of their active time in moderate MI between the high and low seasons, even though their average amount of MI decreased. The farmers' percentage fluctuated between seasons, with a smaller percentage of time spent in moderate MI during the winter. This finding also supports the assertion that OA risk factors for farmers and ranchers are likely occupation specific, as the percentages of time spent in moderate MI correspond with the demands of the seasonal tasks rather than staying consistent throughout the year.

The unique work activities of the farmers and ranchers became evident by comparing the self-recorded work logs for both groups. The farmers showed a marked increase in irrigation, fieldwork, and general chores during the high season, activities that coincide with potential OA risk factors (29, 30). In the low season, however, growth cycles and frozen soil forced farmers to halt field cultivation, and the farmers' activity logs were more heavily weighted towards personal needs, non-agricultural activities,

and maintenance activities. The ranchers daily recorded direct interactions with animals, especially cattle, throughout the high season. During the low season, they recorded similar maintenance activities as the farmers, but also continued to work regularly with the livestock. Although the intensive work of branding or calving paused during the low season, the animals still required feeding, handling, and tending during the winter. While the farmers' high-season work included movements with associated OA risk factors (e.g., irrigation work, field work), these unique activities were largely restricted or discontinued during the low season. In contrast, as the ranchers spent greater amounts of their typical workday with large animals and continued to perform this work throughout the low season (albeit to a lesser degree), the danger of animal-related injury (35), and thus potential OA development, was a constant factor (34).

The mixed-effects analyses that focused on pain indicated that the two groups showed opposite seasonal responses to their pain, with the ranchers' pain decreasing during the low season and the farmers' pain increasing, although this relationship was only trending towards significance. This seasonal variation in perceived pain may suggest that the perceived joint pain in both groups may be affected by the types of tasks each group does in their high and low season. As a post-hoc analyses failed to detect significant relationships between MI percentages and KOOS, however, further investigation is required to understand why the farmers and ranchers experienced opposite results and how their specific tasks or activities affect their perception of joint pain.

This one-year investigation was limited to Montana farmers and ranchers who agreed to participate. Geographic challenges and varying extremes of seasonal climate typical to this area may have affected the MI in either group compared to other agricultural locations or years. Additionally, while KOOS scores were recorded to understand the effects of OA on movement data (47), the study eligibility criteria did not control for OA diagnosis. Finally, although the waist-worn sensors provided

accelerometer data, they were not sufficiently capable of detecting awkward or dangerous movement patterns (e.g., extreme knee flexion (48)) that could be associated with OA development.

## Conclusion

To better determine why agricultural workers appear to be particularly affected by OA, this study investigated the activity levels of two agricultural subgroups, namely farmers and ranchers. The results indicated that the farmers experienced a greater fluctuation in moderate MI levels from the low to high season with less vocation-unique activities occurring during the winter, whereas the ranchers maintained elevated activity levels throughout the year in their consistent cattle-related tasks. Further research should investigate the direct connection of these movements and activity fluctuations to OA development to determine whether agricultural-related OA tendencies are connected to job-specific movements or to the types of activity common to both farming and ranching.

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# CHAPTER 3

# EFFECTS OF COGNITIVE CHALLENGES ON TIBIOFEMORAL CONTACT FORCES DURING GAIT AND KNEEL-TO-STAND MOVEMENTS

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# EFFECTS OF COGNITIVE CHALLENGES ON TIBIOFEMORAL CONTACT FORCES DURING GAIT AND KNEEL-TO-STAND MOVEMENTS


## Abstract

Although deep flexion movements (e.g., kneeling) have been connected to osteoarthritis, characterizations of the tibiofemoral contact forces during unilateral kneel-to-stand transitions have not been established. Additionally, the effects of cognitive challenges reflecting real-world multitasking scenarios on contact forces remain unclear. The purpose of this study was to characterize tibiofemoral contact forces for single (i.e., movement only) and dual-task (i.e., movement plus cognitive challenge) conditions during gait and unilateral kneel-to-stand transitions in a healthy population. We hypothesized that dual-task conditions would correspond with increased peak tibiofemoral contact forces and that these peak loads would occur farther from the joint center on the mediolateral axis for dual-task conditions. 3D kinematic and force plate data were collected from 35 healthy, active adults (28 males, 7 females; 26 ± 8 years; BMI 24.4 ± 4.7 kg/m$^2$) for single- and dual-task conditions of gait and kneel-to-stand. Musculoskeletal modelling was used to estimate tibiofemoral contact forces and their estimated knee joint center of pressure. Linear mixed-effects models (fixed factors: movement type (i.e., normal gait or kneel-to-stand), condition (i.e., single- or dual-task), and movement type*condition) indicated that condition ($p=0.291$) and movement type-by-condition ($p=0.356$) had no significant effect on peak contact forces, but kneel-to-stand transitions resulted in higher forces than gait ($p<0.001$). The peak tibiofemoral contact force center of pressure was significantly affected by movement type ($p<0.001$) and movement type*condition ($p = 0.038$), occurring more medially for kneel-to-stand transitions than gait tasks, and located closer to the joint center during dual-task conditions. These findings suggest that kneel-to-stand transitions disproportionately load the medial portion of the knee and that dual-task conditions influence only the distribution (not the magnitude) of peak tibiofemoral contact forces.

## Introduction

Osteoarthritis (OA) is a disease that results in joint cartilage degradation and annually results in over $89 billion in healthcare costs for Americans alone.[1-4] While OA affects millions of people specific populations, team sport athletes and manual laborers—especially agricultural workers[5]—appear to have relatively high risk compared to the general population.[6,7] Individuals with OA demonstrate observable movement alterations (e.g., decreased knee extension moments and angles while walking)[8,9] known as biomechanical biomarkers of OA. Although correlations exist between OA progression and compensational movement strategies, kinematic and dynamic variables have failed to establish a causal relationship with OA[10-15], most likely because joint contact loads are the mechanical driver of OA movement characteristics.

After OA initiation, continued loading of the damaged cartilage can result in OA progression.[16] Knee joint articular cartilage degradation coincides with increases in medial tibiofemoral contact forces until the cartilage has completely degraded and the tibia and femur grind together.[17-19] Knee joint contact forces have been thoroughly studied for walking gait through instrumented prosthetic knee measurements and musculoskeletal modeling techniques which estimate the forces from muscle activations on the joint. [20-22] However, contact forces in movements specific to at-risk populations are not as well understood. Deep flexion movements (e.g., kneeling or squatting) are common in manual labor and are known to result in higher contact forces than walking gait.[23] Connections between manual labor, excessive joint loading, and OA development make deep flexion movements of particular interest,[16,24,25] but studies that have investigated these movements are vague or conflicted.[26-28] Where internal contact forces have been estimated, the effects of cognitive distractions on these loads such as during work activities (e.g., framing or calving) have not been described.[23]

Biomechanical studies can artificially cause participants to focus on common daily movements, resulting in increased speed and stability that is not representative of their natural movement.[29-32] This

focus can be mitigated in movement studies through the use of cognitive challenges (i.e., dual-tasks), especially visual challenges,[33] which require participants to complete some mental challenge while moving.[34,35] Go/No-Go conditions,[36] memorization tasks,[37] and variations of the Stroop test[38] are commonly used to probe action inhibition, multitasking, and similar aspects of executive function that impact movement.[39-41] Depending on the movement and challenge, dual-tasks can result in reduced stability, decreased movement speed, and increased muscle activation,[42-45] normalizing studied movements to those of daily life.[29] However, a knowledge gap exists regarding the effects of dual-task conditions on tibiofemoral contact forces. Establishing a relationship between the magnitude and location of contact forces, movement type, and cognitive loading will provide a framework for understanding OA risk and development in real-life scenarios of high-risk groups such as athletes and manual laborers.

Therefore, the purpose of this study is to examine differences in tibiofemoral contact forces during single and dual-task conditions within normal gait and unilateral kneel-to-stand transitions in a healthy population. As OA progression is influenced by excessive loads, this study has focused on the peak tibiofemoral contact force in each trial. Because increased medial contact forces are associated with OA progression and dual-task conditions are associated with decreased stability, our study also investigated the center of pressure in the knee joint (COPk). Our primary hypothesis was that the dual-task condition would result in an increased peak tibiofemoral contact force during both the normal gait and the kneel-to-stand dual-task trials. Our secondary hypothesis was that that the COPk at peak tibiofemoral contact force would be positioned farther from the joint center on the mediolateral axis during dual-task conditions for both movement types.

## Methods

In order to be eligible, participants were required to be physically active, healthy adults between 20 and 60 years old, as defined by having a Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) pain score <2[46,47], no history of lower body torn ligaments or surgery, no lower body injury in the past three years, a Tegner activity scale>3[48], and a willingness and capability to complete all movements in the study protocol. The WOMAC pain score limitation was meant to remove participants who might be experiencing joint pain due to OA.[49] The limitations on previous surgeries or torn ligaments were intended to avoid the population having an OA initiation event that might affect their movement, and the limitation on injuries in the past three years was intended to prevent injury-caused movement alterations. The Tegner scale range allowed for participants who are at least recreationally active; the minimal activity level is defined as a participant being currently able to cycle, cross-country ski, or jog at least twice weekly. A sample size of n=33 was calculated using General Linear Mixed Model Power and Sample Size (GLIMMPSE, version 3.0) for a 0.8 target power with the type I statistical error coefficient $\alpha = 0.05$,[50] based on results from the Astephen et al.,[51] McLean et al.,[52] and Dai et al.[53] studies (see Supplemental Table 3.1 for power analyses inputs).

Prior to the motion capture session, participants completed the self-administered short form of the International Physical Activity Questionnaire54,55 (IPAQ) at the beginning of the test protocol. This questionnaire classifies participant activity levels into low, medium, and high during the prior two weeks. For the motion capture session, ten motion capture cameras (six Raptor and four Kestrel Motion Analysis cameras) collected data at 250 frames per second and five force plates collected at 1,000 Hz. Sixty reflective markers were placed on anatomical and tracking landmarks based on the marker set by Graham et al.56 prior to static calibration (Figure 1a-b). In brief, this marker set included tracking clusters on the thighs and shanks and individual markers on the metatarsals, calcanei, ankles, femoral condyles, and iliac crests, as well as assorted markers on the upper body.

For the walking trials, participants started at a fixed position at one end of the laboratory space and were instructed to walk normally across the laboratory space while staring at a fixation cross (Figure 3.1c). Two to four unrecorded trials were conducted to allow the participants to become accustomed to the laboratory space and to ensure that the participants would achieve full foot contact with the force plates while maintaining visual fixation (i.e., good trials). Once these test walks were completed, data were recorded for three good trials. Participants were then asked to continue the walking trials while completing the dual-task condition of a visual Stroop test.[38] For this Stroop test, the participant was presented with a series of words stating a color (e.g., green, yellow, or blue) in a font color that was either congruent or incongruent with the word, with each word appearing for 2 seconds on a 54-inch television. The participant was asked to state the font color of the word as soon as they could while continuing to walk across the laboratory space. This test was chosen because it could be performed continuously throughout the walking trial while requiring sustained attention. One unrecorded training trial was completed to familiarize the participant with the Stroop test, after which three good trials were collected. During gait trials, the participant started walking several paces before making contact with the force plates, removing potential effects of dominant or non-dominant starting limb.

The single-task kneel-to-stand movement required participants to kneel with one knee on a force plate with the toes of the kneeling limb on a force plate directly posterior to the first, and the foot of the non-kneeling limb resting on a third force plate (Figure 3.1d). Participants' arms were to remain at their sides to avoid providing support during the movement. On the participant's initiative, they stood as quickly as they could, replacing their knee with their foot as they stood. For the dual-task condition, two FitLight sensors were placed peripherally at eye level with the kneeling participant with a third sensor positioned in front of the participant. The peripheral sensors blinked random colors, which the participant was instructed to ignore until a predesignated "go" color flashes. Upon seeing this color, the participant stood as quickly as possible while memorizing a sequence of three colors flashed from the

FitLight sensor in front of them. Upon standing, the participant immediately repeated the pattern of colors (e.g., “Yellow, blue, purple”). This test was chosen because, unlike the Stroop test, it could be completed during the relatively short kneel-to-stand trial while still taxing the executive function. Two to four unrecorded trials were conducted prior to three recorded successful trials to mitigate learning effects. During the kneel-to-stand trials, the weighted limb was randomized until three successful trials of the dominant limb were collected.

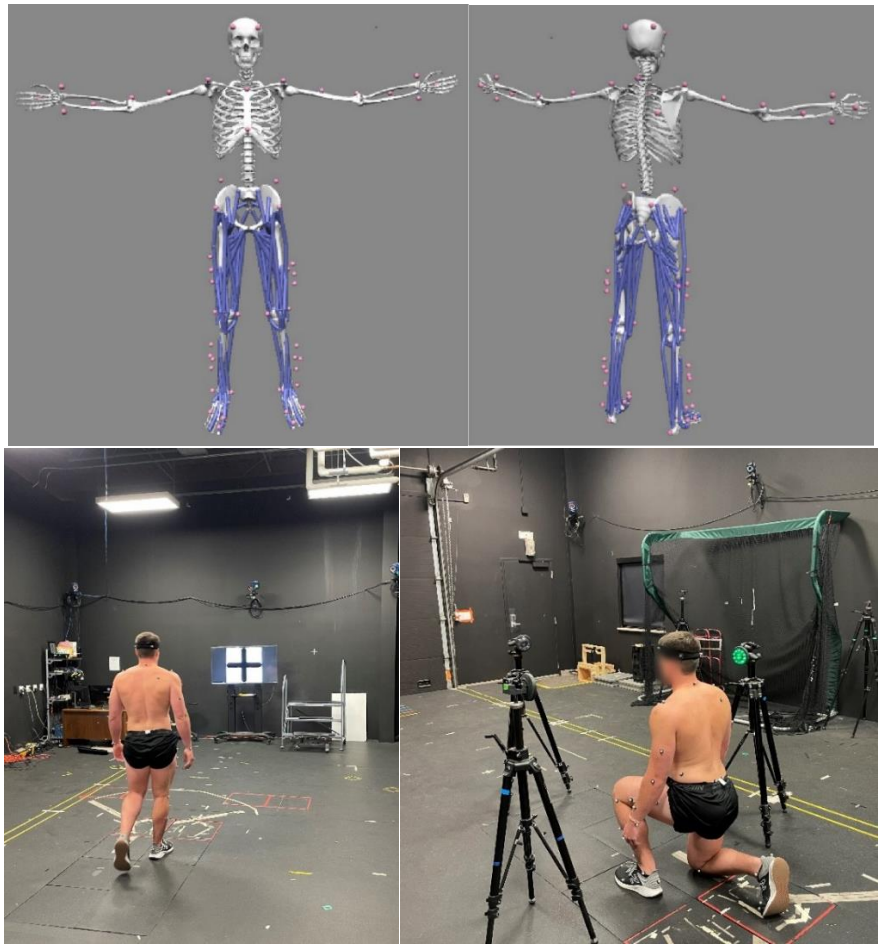

Figure 3.1a-d. Marker Set and Movements. Figures 3.1a-b show the marker set and musculoskeletal model in static pose. Figures 3.1c-d depict a participant in single-task gait and dual-task kneel to stand, respectively.

Each participant's walking and kneel-to-stand motion capture data was low-pass Butterworth filtered with a cutoff frequency of 6 Hz and analyzed at a 250 Hz timestep using a scaled Catelli OpenSim musculoskeletal model[22,57,58] which has been validated for normal gait and deep hip and knee flexion. This model is a derivative of the Rajagopal model,[59] which optimizes muscle strengths based on MRI scans of healthy adults, as well as optimized fiber lengths and pennation angles based on cadaveric scans. The Catelli model was adapted from the Rajagopal model using in-vivo and cadaveric MRI scans to dictate muscle wrapping around the knees, more accurately representing deep knee flexion. Important to the current study, the model has a strong parameterization of the knee joint and tibiofemoral contact loads. Inverse kinematics, inverse dynamics, and static optimization were performed in OpenSim using an analysis methodology from Graham et al.[56], from which the tibiofemoral contact force and COPk for the dominant limb knee (defined as the limb a participant would choose to use when kicking a soccer ball as hard as they could) were estimated throughout the stance phase of each trial. Forces were normalized by body weight. Horizontal movement speed for the walking trials and vertical rising speed for the kneel-to-stand transition were calculated from the pelvis tracking data to identify differences in movement speed and consider it as a covariate in statistical analyses. Analysis for the walking trials began at the heel strike of the dominant limb (defined as a vertical ground reaction force ≥20 newtons) and terminated just prior to initial contact of the contralateral limb thereby focusing analysis on periods of single-limb stance. Trials for the kneel-to-stand transition initiated at the removal of the non-dominant limb's knee from the ground (defined as a ground reaction force <20 newtons on the force plate) and terminated just prior to the non-dominant limb's foot strike. Trials were time-normalized for both movements.

Although the Catelli model does not partition tibiofemoral contact forces into lateral and medial components, the COPk can be used as a coarse surrogate for medial versus lateral bias in tibiofemoral loading. COPk per time-step in the tibiofemoral contact plane was calculated by dividing the sagittal and

frontal plane internal knee moments (defined relative to the tibia coordinate system) by the axial force at the knee joint center for each time point.[60] These COPk calculations were normalized across participants by dividing the distance (mediolateral and posterior-anterior axes) by the tibiofemoral scaling factor for the participant. Forces and moments were resolved in the tibial coordinate system, which yielded COPk estimates in the tibial coordinate system.

The effect of the movement type and condition on the peak tibiofemoral contact forces and their mediolateral distances from the joint center were analyzed using linear mixed-effects statistical models. Age, sex, BMI, movement type-by-condition, and speed-by-movement type were considered as potential covariates. Model selection was informed by adjusted $R^2$, Bayesian information criterion (BIC), and Akaike information criterion (AICc) values to determine the best fit model for each variable.[61,62] Cohen's d effect sizes were calculated to determine how large of an effect the movement type and condition had upon the variables of interest. Finally, *post hoc* statistical parametric mapping analyses (SPMf) were performed using the SPM1D version 0.4 open-source code (www.spm1d.org) comparing the tibiofemoral contact forces for single- and dual-task conditions, with the movement types considered separately. SPMf analysis creates a statistical test continuum from a series of analyses of variance tests taken at each time point and then quantifies the probability that the continuum would exceed the alpha=0.05 threshold (f*),[63] allowing the entire trial to be analyzed for variance rather than only specified force values (i.e., peak contact force).

## Results

Thirty-five healthy, active adults provided Institutional Review Board-approved informed consent to participate in the study (28 males, 7 females; 26 ± 8 years; BMI 24.4 ± 4.7 kg/$m^2$). Of these 35 participants, ten were manual laborers (e.g., agricultural laborers and firefighters) and twenty-five were recreationally active, as defined by a minimum Tegner activity score of four. IPAQ activity level

classification can be seen in Table 3.1. One of the two low-activity participants was an off-season farmer. Data from two participants' single-task gait trials and three participants' single-task kneel-to-stand trials were excluded due to post-processing identifications of poor foot strikes and musculoskeletal model constraint violations, respectively. The tracking markers' root mean square (RMS) error for the full-body musculoskeletal model averaged 2.23 cm (SD=0.40 cm), and the total squared error averaged 2.28 cm (SD=0.86 cm) across all trials, falling within acceptable standards.[64]

| IPAQ Classification | Classification Requirement | Number of Participants |
|---|---|---|
| High | At least 1500 MET-minutes/week from vigorous activity within 3 days OR 3000 MET-minutes/week from walking moderate, or vigorous intensity within past 2 weeks | 21 |
| Medium | At least 30 minutes per day of vigorous activity for 3 days, OR of moderate activity and/or walking for 5 days, or at least 600 MET-minutes/week within past 2 weeks | 8 |
| Low | Failure to qualify as medium or high activity | 2 |
| Not Recorded | N/A | 4 |

Table 3.1. Summary of Participants' IPAQ Scores and Activity Classification Cutoffs.

The peak axial tibiofemoral contact force for normal gait (mean=5.09 BW, SE=0.08 BW) occurred during push-off just prior to the non-dominant limb's heel strike, whereas the peak axial force for the kneel-to-stand transition (mean=9.70 BW, SE=0.20 BW) occurred prior to the non-dominant foot leaving the force plate. The best-fit mixed-effects model (Supplemental Table 3.2) for the dependent variable of peak axial tibiofemoral contact forces in the dominant limb (Figure 3.2a-b) indicated the fixed factor of movement type (i.e., normal gait or the kneel-to-stand transition) to be significant ($p<0.001$, $d=3.7$),

although neither condition (i.e., single- or dual-task) (p=0.291), nor the movement type-by-condition interaction (p=0.356) were significant. The model found both BMI (p<0.001) and a speed-by-movement type interaction (p=0.010; see Table 3.2) to be significant covariates, with lower BMI being associated with higher contact forces.

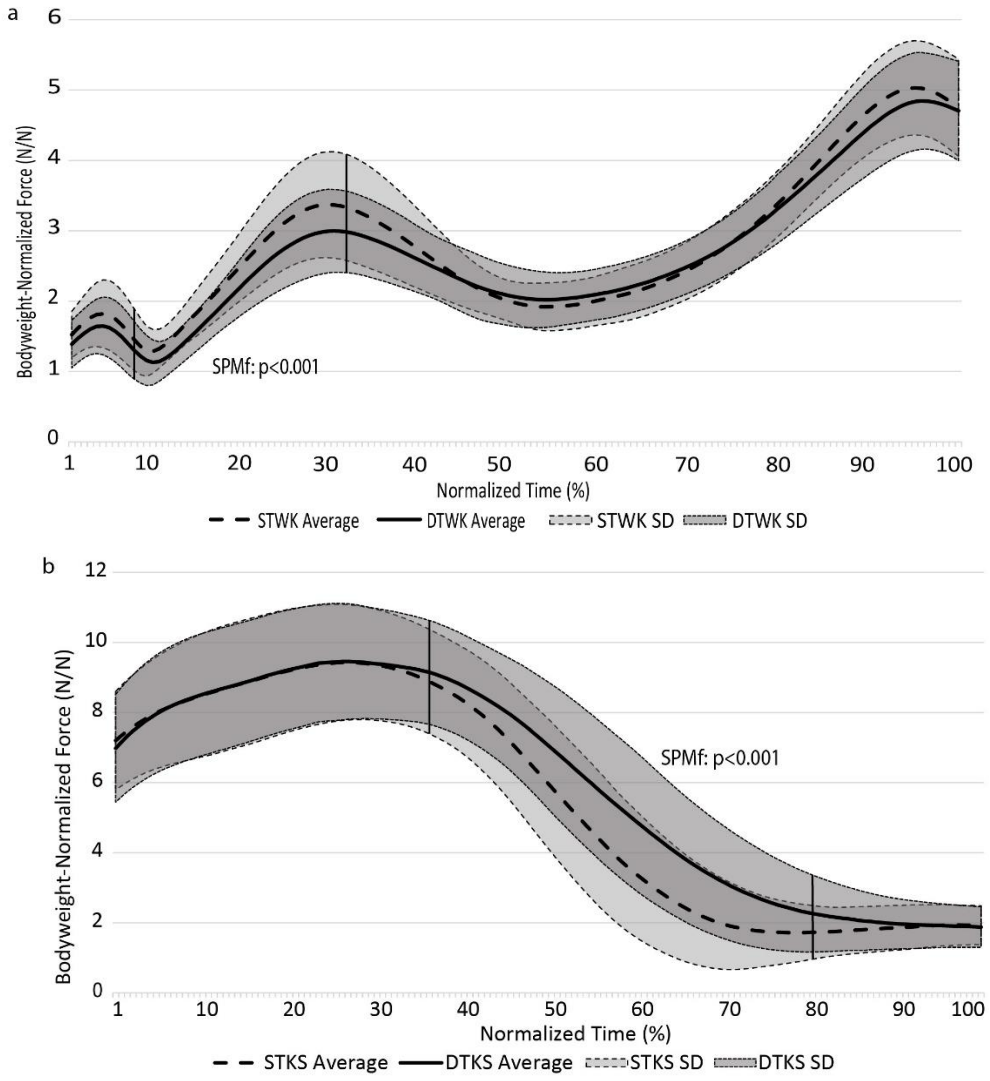


Figure 3.2a-b. Tibiofemoral Contact Forces during Single-Limb Stance in the Dominant Limb for Normal Gait (3.2a) and Kneel-to-Stand (3.2b). Periods within the vertical lines on each graph indicate SPM significance.

| Movement | Single Task | Dual Task |
|---|---|---|
| Gait Speed (m/sec) | 1.37 (0.03) | 1.25 (0.03) |
| Kneel-to-Stand Vertical Speed (m/sec) | 0.69 (0.02) | 0.72 (0.02) |

Table 3.2. Summary of Average and Standard Error of Movement Speeds.

The COPk maps for each participant can be seen in Figure 3.3, with the COPk at peak axial contact force denoted. A second mixed-effects model was used to determine differences in medial-lateral application of the peak forces, with the mediolateral axis COPk at the peak axial contact forces as the dependent variable. Movement type was a significant factor ($p<0.001$, $d=8.4$), as was the movement type-by-condition ($p=0.038$, $d\leq0.3$). During the walking trials, the COPk at peak axial contact force was lateral to the joint center (mean=7.8 mm, SE=0.2 mm). The corresponding COPk for the kneel-to-stand transition was medial to the joint center (mean=-6.8 mm, SE=0.2 mm). Regarding the movement type-by-condition interaction, the COPk at peak axial contact force during the walking trials for the single-task condition (mean=8.0 mm, SE=0.3 mm) was more lateral than the dual-task condition (mean=7.7 mm, SE=3.0 mm), whereas during the kneel-to-stand transition the COPk was more medial during the single-task condition (mean=-7.0 mm, SE=0.3 mm) than during the dual-task condition (mean=-6.5mm, SE=0.3 mm). Finally, the covariate BMI ($p<0.001$) was also found to be significant in the best fit model.

The *post hoc* SPMf analyses found a significant difference in the walking conditions ($p<0.001$, $f^*=10.560$) during 10-34% of stance phase (Figure 3.2a), with single-task conditions associated with larger contact forces. Similarly, the SPMf analysis of the kneel-to-stand transition found significant differences between conditions ($p<0.001$, $f^*=8.806$) during 36-81% of the transition (Figure 3.3b), with dual-task conditions associated with larger contact forces.

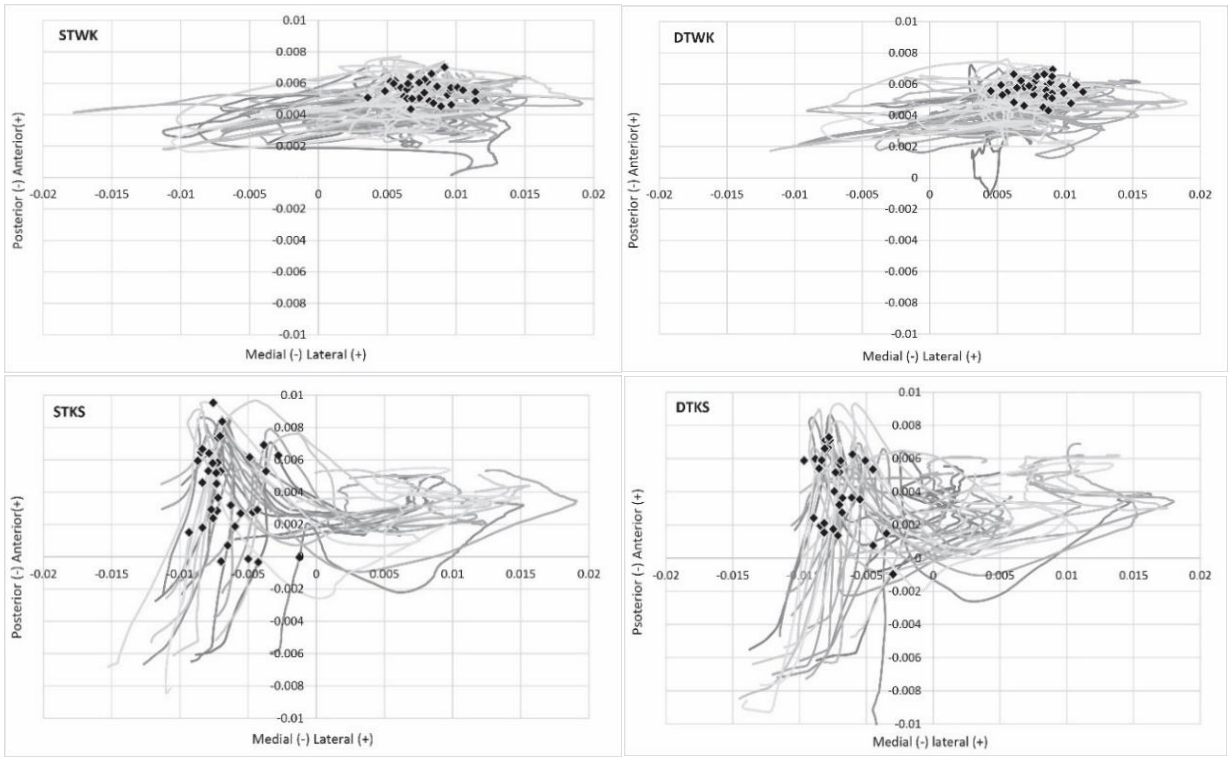


Figure 3.3a-d. Knee Joint Center of Pressure Path Throughout Single- and Dual-Task Gait (STWK and DTWK) and Kneel-to-Stand (STKS and DTKS) Trials. Paths have been normalized by each participant's musculoskeletal scaling factor. The origin represents the knee joint center. Axis units are in meters. Diamond markers indicate the location of the center of pressure at peak contact force.

## Discussion

The purpose of this study was to evaluate differences in tibiofemoral contact forces for single and dual-task conditions during normal gait and unilateral kneel-to-stand transitions in a healthy population. Contrary to our hypothesis, condition (i.e., single- versus dual-task) was not significantly related to either the peak tibiofemoral contact force or the mediolateral COPk. This lack of significance is surprising, as other studies have shown that the introduction of a dual-task can affect movement parameters such as adduction moments and joint angles.[51,52] The cognitive challenges used in this study may also have significant effects on peak joint contact loads that are not discernable without partitioning out the medial and lateral joint force components. The changes in movement speeds between the single- and dual-task conditions may have introduced enough variability that differences in

contact force magnitudes were more difficult to detect.[65] Additionally, the SPMf analysis results indicate that the challenges may have instigated changes to loading rates rather than peak force values; it is possible that different challenge difficulties or methods could have more significant effects on the peak contact forces.

The differences in peak contact forces across movement types (i.e., walking versus the kneel-to-stand transition) supports the argument that deep flexion movements pose a high risk of excessively loading medial, unconditioned cartilage. [24,25] During this study's kneel-to-stand transition trials, the peak axial tibiofemoral contact forces were 90% larger than those of normal gait, or on average 9.7 BW. These forces were those estimated from a controlled laboratory environment; although the movement initiation was prompted during dual-task conditions, participants were standing straight up with no added weight. Especially when considering manual laborers who may perform less-controlled kneel-to-stand movements while carrying heavy loads[66], the medially-centered high tibiofemoral contact forces found in this study suggest that deep-flexion movements may hold high risk for OA initiation[67] and progression.[16]

Although movement type-by-condition was a significant factor in the mediolateral position of the COPk at peak tibiofemoral contact force, the effect sizes between single-task and dual-task conditions for the walking trials was low (d=0.16) and the results indicate more lateral loading for the single-task condition versus loading closer to the joint center for dual-task conditions at the time of maximum axial tibiofemoral contact force. The effect size between single- and dual-task conditions for the kneel-to-stand transition was larger (d=0.31) and the effects also indicated loads closer to the joint center during dual-task conditions. However, the COPk at peak contact force was generally lateral to the joint center for gait and medial for kneel-to-stand, further suggesting that kneel-to-stand poses larger risks for loading unconditioned cartilage.

In order to avoid additional inhibitions to natural movement, this study treated movement speed as a covariate rather than a controlled parameter. During the normal gait trials, average horizontal speed decreased during the dual-task Stroop tests, as expected from similar study findings.[68] During the kneel-to-stand transition, however, movement speed increased during the dual-task condition, perhaps resulting from greater urgency imposed by the 'Go/No-Go' component of the dual-task condition.[36,69] The visual Stroop test required ongoing color and word differentiation that could be performed throughout the gait trials, whereas the kneel-to-stand dual-task condition was selected to meet the shorter movement time of kneel-to-stand. However, key differences exist between the challenges that inhibit between-movement comparisons of dual-task conditions.

The peak compressive tibiofemoral contact forces for the walking trials were estimated by the Catelli model as 5.1 BW, located in the push-off phase of normal gait. This estimate is consistent with Kotsifaki et al.'s report of 5 BW contact forces during walking gait using a modified version of this model.[20] Notably, 5 BW is higher than the 3 BW estimate of other models and instrumented prosthetics.[21,70] However, we are confident in the methodology of our study. The vertical ground reaction forces (average=1.16 BW, SE=0.01 BW for walking) for our study are considered typical for walking gait, as are the relative activations of lower body muscle groups at peak knee contact force (Supplemental Figure 3.1). The inverse kinematic RMS and total squared error was within acceptable tolerances and the reserve actuator averaged only 0.39% of the ankle, knee, and hip joint moments across walking trials. The Catelli model has been validated for the types of movement performed in this study;[22] and the Kotsifaki et al. group have reported similar tibiofemoral contact forces during normal gait.[20] These checks indicate that the elevated contact force estimate of our study is most likely due to parameterizations unique to the Catelli model; however, we consider the results of this study insightful for comparing the relative loads of walking gait to the kneel-to-stand transition.

Although cognitive challenges did not greatly alter peak contact forces, a comparison of the contact forces throughout the stance phase (Figure 3.3a-b) appeared to indicate that the average contact forces may have been different between conditions. This led to the exploratory *post hoc* SPMf analysis comparing the tibiofemoral contact forces for single- and dual-task conditions. The results of this analysis indicate that while the peak contact forces may not have differed significantly across conditions, the dual-task conditions may have effects on loading rates and impulse loading, factors strongly associated with OA development.[71-73] As such, further studies are merited to confirm these *post hoc* findings.

This study was focused on healthy participants and can make no claim regarding OA development. Movement type and condition were not randomized; however, systematic effects were not anticipated to factor into the study findings due to the differences in dual-task conditions and movement types. Catelli model contact force estimates can be higher than those typically reported, meriting caution when comparing our results to cross-model estimations. Finally, SPMf analysis cannot account for potential covariates such as movement speed which might explain the variance between movement conditions; therefore, further investigation is required to establish the effects of cognitive challenge on contact force loading rates.

## Conclusion

To better understand the relationship between OA biomarkers and movement, this study sought to establish a relationship between movement type, cognitive challenges, and knee joint forces. The results indicate that standing from a unilateral kneeling position loaded more of the medial portion of the knee joint than during normal gait, but that cognitive challenges had little effect on the position or magnitude of these peak contact forces. *Post hoc* analyses suggested that further investigation should

be made into the differences in tibiofemoral contact forces between single- and dual-task conditions throughout the entire kneel-to-stand transition.

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# CHAPTER 4

# GENERAL DISCUSSION AND CONCLUSIONS

## Key Takeaways

The purpose of this thesis is to provide insight regarding which factors should be considered in developing a relationship between agricultural work and OA initiation by investigating the following questions: 1) What activities patterns characterize the distinction between farming and ranching work? 2) What are the characteristic knee joint mechanics in movements common to agricultural work? The two studies of this thesis resulted in the following key takeaways.

### Study 1

- Both farmers and ranchers had an increase in average movement intensity during their high seasons of work compared to low seasons.
- Farmers had greater seasonal fluctuations in the percentage of time spent in moderate intensity activities while ranchers maintained more consistency over seasons.

### Study 2

- Cognitive Loading:
    - Dual-task conditions had little effect on the magnitude or COPk location of peak tibiofemoral contact forces.
    - Dual-task conditions resulted in decreased early stance-phase tibiofemoral contact forces for walking gait, possibly driven by reduced walking speeds associated with the dual-task.
    - Dual-task conditions resulted in increased tibiofemoral contact forces in the kneel-to-stand transition after peak, possibly driven by increased urgency associated with the dual-task.

- Kneel-to-stand transitions resulted in higher, more medial tibiofemoral contact forces than walking gait.

These studies were designed to fill fundamental knowledge gaps that are foundational to understanding potential factors involved in the disproportionately high rate of OA in agricultural workers. The first study quantitatively characterized differences in patterns of physical demand between farmers and ranchers. The second study determined the effects of real-world challenges during agricultural work (i.e., cognitive distraction and deep flexion movements) on tibiofemoral contact forces. Taken together, these studies provide insight into how agricultural occupations and environments can affect knee joint mechanics, a critical step in characterizing OA risk in agricultural workers.

## Potential Risks for Farmers and Ranchers

Although general agricultural work is associated with OA development,[1] there is some disagreement on whether farming presents a greater risk than other manual labor occupations, most of which involve some level of deep-flexion movements. Holmberg et al.'s study indicated that, once adjusted for such factors as smoking and injury, men who worked on farms had lower odds of developing knee OA than construction workers with the same amount of work experience.[2] When compared to non-manual labor occupations, farmers are still three times as likely to develop OA.[3] However, Thelin et al. posit that ranchers, specifically dairy farmers, are 45% more likely to develop OA than other manual labor occupations.[4] Compared to non-agricultural work, general agricultural work is associated with an increased likelihood of OA development; while the risk appears to be elevated in the case of ranchers, it is likely that both farming and ranching have associated risk factors that are unique to these occupations.

In chapter 2 of this thesis, we found that both the seasonal activity patterns and types of activities being performed by farmers and ranchers clearly differed from each other. Farmers fluctuated

between increased levels of work activity in their high season and minimal agriculturally-related work in their low season. Ranchers consistently spent a larger percent of their time performing tasks of moderate intensity levels, working with livestock throughout the year. While definite connections between these patterns and OA development would require long-term observational studies, the difference in activity patterns between farmers and ranchers support the idea that these occupations hold at least some distinct OA risk factors.

Joint trauma is one of the prevailing factors of OA development[5] and presents a clear risk for ranchers. The ranchers reported year-round interactions with their livestock, often entering pens in order to brand, medicate, or move their animals. This consistent interaction with animals corresponded with a similar percentage of their time spent in moderate movement intensity throughout the year. Joint trauma is a common occurrence for livestock workers;[6] each time a rancher is in close proximity to livestock they risk getting kicked, pushed, or tripped, with the results ranging from minor bruises to torn ligaments, broken bones, or death.[7] The risk of injury is compounded as the ranchers are often forced to squat, kneel, or bend over while working, putting them in a compromised position prior to any sudden movements from the animals. Both farmers and ranchers perform manual labor outdoors on uneven terrain, which may pose additional risk of potential injury.[8] However, ranching involves regular interaction with unpredictable livestock, putting them at heightened risk for injury, which could instigate future OA progression.

Farmers do not have the same risks associated with livestock, but the seasonal fluctuation in their movement intensity could have negative implications for OA risk. Farmers' low seasons were largely characterized by non-agriculturally related projects requiring low percentages of moderate physical activity. Tibial cartilage has been shown to atrophy up to 9% within seven weeks of reduced joint loading in patients with ankle injuries,[9] meaning that farmers who reduced their activity levels throughout the winter may not maintain the cartilage conditioning required to safely perform the

intense manual labor of their high work season. The high season activity of the farmers provides ample opportunity for OA initiation through the excessive loading of unconditioned cartilage.[10]

On the other hand, the extended periods of reduced activity may be beneficial to farmers who have undergone excessive strain or injury during their high work seasons. In sports applications, soleus muscle strains have been reported as requiring up to 41 days for recovery.[11] However, damaged articular cartilage or subchondral bone has little chance of healing naturally.[12] Ranchers who maintain elevated activity levels year-round do not have extended periods of rest necessary to recover from excessive muscle or ligament use. Farmers, on the other hand, have this recovery period every low season, although the rest period is unlikely to repair cartilage damage. The effects of seasonal agricultural work on injury rate and OA-development have not been established; it may be that the seasonal fluctuations activity pattern of farmers has multiple, interacting effects on OA. Regardless, the differences in seasonal activity levels between farmers and ranchers indicate distinctive risk factors for each group.

Although several of the risks associated with farming and ranching may stem from different causes, one shared risk comes from the deep flexion movements, which are inherent to both occupations as they lift heavy objects from the ground, repair equipment, and climb over fences or vehicles. Even in the controlled laboratory environment of our biomechanics study, unilateral kneel-to-stand transitions resulted in contact loads twice as high as those of gait and these peak contact forces were biased to the medial compartment of the knee joint, compounding the risk of unconditioned cartilage loading.[13] For both farmers and ranchers, this force could be further increased by lifting heavy objects, which is common in these professions. Ranchers are especially at risk of excessively loading unconditioned cartilage when they are forced to stand up in response to sudden livestock movement, as supported by the magnified medial loading and increased loading for portions of the stance phase during the dual-task knee-to-stand movement in Chapter 3.

The Go/No-Go dual-task condition of the kneel-to-stand movement was used to help recreate these types of unanticipated movements. This condition only caused the movement initiation time to be unanticipated, however, and did not prompt participants to alter movement speed or direction; participants were requested to stand straight up at maximum speed for all kneel-to-stand trials. Still, this dual-task condition helped bridge the gap between established, controlled biomechanical studies and the more hazardous environment of livestock handling. The results of this study indicate that sudden movement initiation prompts (i.e., a Go condition or a moving cow) impact tibiofemoral contact forces, although this impact is not necessarily seen at peak force.

One further note should be made regarding these studies and any potential connection to OA. The first study was focused on evaluating the movement intensity of farmers and ranchers, while the second compared the knee mechanics of single- and dual-task conditions in a healthy population. As such, these studies make no claim to causal analyses of OA development. For instance, we did not record numbers of accidents or injuries reported on the agricultural operations; any such record would most likely have been insufficient to draw conclusions from given the brevity of the study period. However, when discussing potential links between OA and agricultural work, injury from equipment malfunction cannot be ignored. Tractor turnovers can be at least as injurious as livestock work and farming injuries may be more common than those of ranching, although many of these injuries are related to the back or torso with varying influence on OA development.[17,18] Long term observational studies would be required to characterize the relationship between injury type, occupation and OA initiation.

## Future Direction

While this thesis helps to fill knowledge gaps regarding occupational-specific movement characteristics and the effects of cognitive challenge on knee joint mechanics, it has also opened several

avenues for future investigation. These avenues include tailoring biomechanical studies to occupational-specific movements and environments, adjusting musculoskeletal modeling to include compartmental contact load estimations, and formulating studies that focus on SPM statistical analyses. Initial work has been completed on some of these aspects, helping to develop a framework for studying agriculturally-related OA progression.

Standing from a kneeling position is not specific to agricultural work; rather, establishing the effects of cognitive challenges on this fairly common deep flexion movement was a necessary first step towards agricultural-specific movements. With this study completed (Chapter 3), a next step is to progress the research to account for more agricultural-specific movements and factors. Such tasks might include fence-climbing, lifting a weight from the ground and placing it on a raised surface (to simulate loading a truck), or lifting one end of a heavy or moving object while bending over (similar to maneuvering an animal). During this thesis, a customized setup was developed to instrument a fence section to obtain reaction forces applied to the foot of a climbing limb during a fence climbing task (Figure 4.1). Preliminary data have already been collected for single-task conditions of weight-lifting and fence-climbing tasks and are positioned to accelerate these impactful extensions of this research.

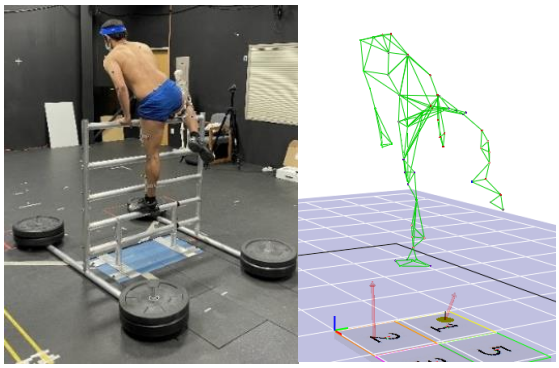

Figure 4.8a-b. Novel Fence Climb Task. 4.1a shows a participant completing the fence climb movement. 4.1b shows the preliminary data from this trial.

The current fence climbing task utilizes a fence rung that is bolted to the force plates and a detached, non-instrumented upper support rung. The main challenge in processing these data will be in determining how to accurately account for participants supporting themselves on the top rung while stepping on the lower rung. Should full-body models be investigated within these trials, studies such as Knarr et al.'s investigation into residual reduction algorithms for handrail use during normal gait[20] will provide the basis for this validation process. Once validated, both loading rates and peak tibiofemoral contact values should be calculated from the fence climb task and contrasted with those of the kneel-to-stand task.

For both gait and kneel-to-stand, we only estimated the tibiofemoral contact forces at the joint center, meaning that changes to medial compartmental loads could not be detected. While the overall peak forces did not differ between dual- and single-task conditions, the distribution of the loads on the lateral versus medial compartments may have significantly changed. Contact forces are often not evenly distributed across the medial and lateral components of the knee; while running, the medial compartment of the knee has been estimated as taking over 50% of the total load during normal gait[21] and over 60% of the total load while running.[22] In order to account for alterations in the relative loading of the knee joint compartments in our data set, a further parameterized model such as that of Bedo et al.[23] must be used. This model is another update of the Rajagopal/Catelli[24,25] model used in our study, making it well suited as the next step in our data analysis. Given the danger of excessively loading unconditioned cartilage, alterations to the distribution of contact loads are particularly important for understanding OA development and should be examined throughout the trial using SPM-analysis.

The *post hoc* analyses for Chapter 3 suggest that rather than focusing on peak contact forces, the forces found during transitional movement phases may provide better insight into the effects of cognitive distraction. During both walking gait and the kneel-to-stand transition, the exploratory SPM analyses found the transitional forces to be significantly different between cognitive conditions (Figure

3.2). Specifically, the forces of the single-task normal gait were higher than those of dual-task conditions prior to and during heel strike. Conversely, after the kneel-to-stand transition's peak force, dual-task forces remained higher than those of the single-task condition. The relevance of mechanical impulse (i.e., integral of force-time time series) to OA has long been established in animal studies[14] and the impulse of heel strikes during human gait have been identified as potential risks for knee cartilage degeneration.[15,16] Morgenroth et al.'s cross-sectional cohort study also indicated a strong relationship between medial tibiofemoral joint degeneration and loading rate during gait.[17] These findings provide strong credence to the benefits of examining both the impulse and loading rates in movements and conditions that increase the contact forces during loading, such as a Go/No-Go condition of kneel-to-stand.

After the movement types, modeling techniques, and statistical methods have been further developed, adjustments should be made to the cognitive challenges, making them more relevant to agricultural work. Visual Stroop tests, such as those used in the gait trials, require participants to multitask but require no physical response to an external stimulus. The secondary task for kneel-to-stand did require responses to external stimuli via the Go/No-Go condition; however, the response was unidirectional. Because ranchers must regularly respond to their livestock, unanticipated directional cues may be a valid method of evaluating the effects of realistic cognitive challenges. The Go/No-Go cognitive challenge could be adjusted to include unanticipated directional cues (i.e., moving forwards, backwards, to one side, or straight up from a kneeling position) rather than simply a Go/No-Go condition.

At least three future studies are immediately feasible based on the work of this thesis: 1) An analysis of the data already collected using a musculoskeletal model capable of estimating compartmental loads. 2) A new study focused single- and dual-task conditions of common agricultural-specific movements (i.e., fence climbing, ground-to-shelf weight-lifting, and bent-over weight-lifting). 3)

A study focused on the effects of unanticipated directional cues for kneel-to-stand movements using both compartmentalized tibiofemoral contact force modeling and SPM analysis. In order to eliminate potentially confounding factors, these studies would need to be performed on healthy, active adults before moving to an OA population. Ideally, the healthy active adults would be agricultural laborers. Unfortunately, recruitment efforts for the previous studies have been stinted in this regard due to the remoteness of the agricultural operations, the time requirements of agricultural work, and the commonality of joint pain and injury in these workers. A mobile motion capture setup may allow biomechanical data to be collected at farms and ranches, reducing the travel barrier for this population.

In order to characterize the baseline effects of occupation, movement type, and cognitive distraction on movement intensity and knee joint contact forces, the studies presented in this thesis have not focused on OA populations. As the relationship between agricultural work and OA progression is developed, tracking the severity and progress of OA development will be critical in determining causal relationships between occupation, injury, and OA initiation. WOMAC pain scores and health histories, while helpful screening tools,[26] will need to be supplemented through MRI informed OA grading[27] and personalized musculoskeletal models.[28] Longer observational studies will also be critical to this process, requiring increased funding and time commitments. In order to offset some of these costs, initial progress has been made in developing these tools for Montana State University's Neuromuscular Biomechanical Laboratory, including complete lower body MRI scans and more detailed knee scans of several participants in the current study.

## Conclusion

By performing quantitative analyses of movement activity levels and qualitative analyses of daily activities for farmers and ranchers in high and low seasons of work, patterns suggestive of OA risk have been developed for both farmers and ranchers. Ranchers may be especially at risk for OA development,

particularly when performing deep-flexion movements in close proximity to livestock. Environmental factors such as unanticipated cattle movement may present additional risk due to increased joint loading rates, as seen by the SPM analysis of the kneel-to-stand movements. The two studies presented here help guide future investigations into occupationally-specific activities and have helped build the foundation necessary for understanding the driving factors of OA initiation in the agricultural community.

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# APPENDICES

# APPENDIX A

## CHAPTER 2 SUPLLEMENTAL INFORMATION

| Participant ID | Sitting MI (g) | Laying MI (g) | Standing MI (g) | Walking Comfortably MI (g) | Walking Briskly MI (g) | Running MI (g) |
|---|---|---|---|---|---|---|
| **P01** | 0.004 | 0.002 | 0.035 | 0.332 | 0.553 | 1.275 |
| **P02** | 0.028 | 0.006 | 0.008 | 0.322 | 0.651 | 1.150 |
| **P03** | 0.038 | 0.002 | 0.007 | 0.315 | 0.583 | 1.343 |
| **P04** | 0.017 | 0.004 | 0.043 | 0.289 | 0.502 | 1.010 |
| **P05** | 0.035 | 0.016 | 0.064 | 0.275 | 0.520 | 1.053 |
| **P06** | 0.020 | 0.001 | 0.035 | 0.292 | 0.731 | 1.208 |
| **P07** | 0.011 | 0.025 | 0.059 | 0.289 | 0.589 | 1.076 |
| **P08** | 0.007 | 0.001 | 0.031 | 0.461 | 0.724 | 1.142 |
| **P10** | 0.020 | 0.002 | 0.046 | 0.374 | 0.627 | 1.284 |
| **Classification:** | Sedentary | Sedentary | Light | Light | Moderate | Vigorous |
| **Average:** | 0.020 | 0.007 | 0.036 | 0.328 | 0.609 | 1.171 |
| **Standard Deviation:** | 0.012 | 0.008 | 0.020 | 0.058 | 0.082 | 0.114 |

Supplemental Table 2.1a. MI Thresholds Pilot Study Averages and Standard Deviations

| | |
|---|---|
| Sedentary - 2σ * | -0.004 |
| Sedentary | 0.020 |
| Sedentary + 2σ | 0.044 |
| **Light Threshold: Greater than the Average of Sedentary + 2σ and Light - 2σ** | **0.128** |
| Light - 2σ | 0.212 |
| Light | 0.328 |
| Light + 2σ | 0.444 |
| **Moderate Threshold: Greater than the Average of Light + 2σ and Moderate - 2σ** | **0.445** |
| Moderate - 2σ | 0.445 |
| Moderate | 0.609 |
| Moderate + 2σ | 0.773 |
| **Vigorous Threshold: Greater than the Average of Moderate + 2σ and Vigorous - 2σ** | **0.858** |
| Vigorous - 2σ | 0.942 |
| Vigorous | 1.171 |
| Vigorous + 2σ | 1.400 |
| * σ = Standard Deviation | |

Supplemental Table 2.1b. MI Thresholds Definitions

| Model Dependent Variable | Fixed Factors | | | | | | Covariates | | | | | | Model Comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group | | Season | | Group*Season | | Age | | BMI | | Sex | | Adjusted $R^2$ (%) | AICc | BIC |
| | Coefficient | p | Coefficient | p | Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | | | |
| Average MI of Active Hours | -0.038 | 0.296 | 0.073 | 0.001 | 0.025 | 0.238 | -0.108 | 0.002 | -0.101 | 0.006 | -0.018 | 0.560 | 67.2 | 8 | 12 |
| | -0.010 | 0.771 | 0.073 | 0.001 | 0.025 | 0.208 | - | - | -0.097 | 0.012 | -0.051 | 0.125 | 70.5 | 9 | 13 |
| | -0.037 | 0.278 | 0.073 | 0.001 | 0.025 | 0.234 | -0.114 | 0.000 | -0.106 | 0.004 | - | - | 67.1 | 3 | 7 |
| | 0.010 | 0.764 | 0.075 | 0.001 | 0.023 | 0.267 | -0.105 | 0.005 | - | - | -0.036 | 0.299 | 69.7 | 10 | 14 |
| | 0.013 | 0.700 | 0.075 | 0.001 | 0.023 | 0.261 | -0.118 | 0.001 | - | - | - | - | 69.8 | 6 | 10 |
| | -0.011 | 0.758 | 0.074 | 0.001 | 0.026 | 0.200 | - | - | -0.111 | 0.004 | - | - | 70.8 | 7 | 11 |
| | 0.027 | 0.426 | 0.075 | 0.000 | 0.023 | 0.234 | - | - | - | - | -0.071 | 0.042 | 71.9 | 10 | 14 |
| Active Minutes in Moderate MI | -0.102 | 0.498 | 0.272 | 0.000 | 0.102 | 0.095 | -0.643 | 0.000 | -0.325 | 0.041 | -0.016 | 0.909 | 87.9 | 159 | 162 |
| | -0.023 | 0.896 | 0.283 | 0.000 | 0.092 | 0.115 | - | - | -0.355 | 0.058 | -0.276 | 0.094 | 89.3 | 181 | 185 |
| | -0.103 | 0.487 | 0.272 | 0.000 | 0.102 | 0.094 | -0.648 | 0.000 | -0.328 | 0.032 | - | - | 88.0 | 157 | 161 |
| | 0.066 | 0.624 | 0.285 | 0.000 | 0.090 | 0.136 | -0.635 | 0.000 | - | - | -0.080 | 0.567 | 87.9 | 165 | 169 |
| | 0.072 | 0.586 | 0.285 | 0.000 | 0.090 | 0.134 | -0.664 | 0.000 | - | - | - | - | 88.0 | 164 | 168 |
| | -0.026 | 0.884 | 0.284 | 0.000 | 0.093 | 0.111 | - | - | -0.435 | 0.020 | - | - | 89.4 | 182 | 186 |
| | 0.137 | 0.392 | 0.294 | 0.000 | 0.081 | 0.157 | - | - | - | - | -0.36 | 0.028 | 89.2 | 188 | 192 |
| Active Minutes in Vigorous MI | -0.208 | 0.281 | 0.148 | 0.162 | -0.016 | 0.881 | -0.824 | 0.000 | -0.290 | 0.143 | 0.332 | 0.068 | 70.3 | 207 | 212 |
| | -0.118 | 0.597 | 0.208 | 0.055 | -0.063 | 0.548 | - | - | -0.337 | 0.154 | 0.016 | 0.939 | 72.0 | 237 | 242 |
| | -0.192 | 0.339 | 0.146 | 0.169 | -0.018 | 0.866 | -0.710 | 0.000 | -0.213 | 0.286 | - | - | 70.9 | 209 | 214 |
| | -0.049 | 0.765 | 0.154 | 0.135 | -0.019 | 0.851 | -0.815 | 0.000 | - | - | 0.268 | 0.127 | 71.2 | 213 | 217 |
| | -0.070 | 0.676 | 0.152 | 0.142 | -0.021 | 0.835 | -0.718 | 0.000 | - | - | - | - | 71.6 | 214 | 218 |
| | -0.118 | 0.592 | 0.208 | 0.055 | -0.064 | 0.547 | - | - | -0.332 | 0.139 | - | - | 72.0 | 236 | 240 |
| | 0.042 | 0.832 | 0.209 | 0.047 | -0.064 | 0.533 | - | - | - | - | -0.070 | 0.726 | 72.8 | 243 | 248 |
| % Active Time—Moderate MI | -0.074 | 0.577 | 0.206 | 0.000 | 0.114 | 0.034 | -0.664 | 0.000 | -0.190 | 0.165 | -0.019 | 0.876 | 88.9 | 143 | 147 |
| | 0.012 | 0.940 | 0.211 | 0.000 | 0.109 | 0.033 | - | - | -0.221 | 0.205 | -0.282 | 0.073 | 90.4 | 168 | 172 |
| | -0.075 | 0.565 | 0.207 | 0.000 | 0.115 | 0.034 | -0.670 | 0.000 | -0.195 | 0.140 | - | - | 89.0 | 141 | 145 |
| | 0.026 | 0.815 | 0.224 | 0.000 | 0.098 | 0.073 | -0.656 | 0.000 | - | - | -0.057 | 0.629 | 87.9 | 148 | 152 |
| | 0.031 | 0.781 | 0.224 | 0.000 | 0.098 | 0.072 | -0.676 | 0.000 | - | - | - | - | 87.9 | 146 | 150 |
| | 0.009 | 0.957 | 0.211 | 0.000 | 0.110 | 0.032 | - | - | -0.304 | 0.085 | - | - | 90.5 | 169 | 174 |
| | 0.115 | 0.434 | 0.226 | 0.000 | 0.094 | 0.069 | - | - | - | - | -0.334 | 0.027 | 89.6 | 174 | 178 |
| % Active Time—Vigorous MI | -0.181 | 0.323 | 0.084 | 0.409 | -0.002 | 0.986 | -0.843 | 0.000 | -0.156 | 0.401 | 0.331 | 0.056 | 69.5 | 202 | 206 |
| | -0.085 | 0.699 | 0.137 | 0.181 | -0.045 | 0.660 | - | - | -0.204 | 0.373 | 0.015 | 0.943 | 71.7 | 233 | 237 |
| | -0.164 | 0.390 | 0.081 | 0.423 | -0.004 | 0.968 | -0.729 | 0.000 | -0.079 | 0.676 | - | - | 70.3 | 205 | 209 |
| | -0.088 | 0.563 | 0.093 | 0.347 | -0.010 | 0.916 | -0.835 | 0.000 | - | - | 0.292 | 0.074 | 69.8 | 207 | 210 |
| | -0.111 | 0.481 | 0.091 | 0.361 | -0.013 | 0.896 | -0.729 | 0.000 | - | - | - | - | 70.4 | 208 | 212 |
| | -0.084 | 0.695 | 0.137 | 0.181 | -0.045 | 0.659 | - | - | -0.199 | 0.360 | - | - | 71.8 | 232 | 236 |
| | 0.019 | 0.920 | 0.143 | 0.153 | -0.050 | 0.614 | - | - | - | - | -0.041 | 0.830 | 72.3 | 238 | 242 |

Supplemental Table 2.2. Full Statistical Analyses of MI Categorization. Highlighted cells indicate best-fit model.

| Model Dependent Variables | Fixed Factors | | | | | | Covariates | | | | | | Model Comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Group | | Season | | Group*Season | | Age | | BMI | | Sex | | Adjusted $R^2$ (%) | AICc | BIC |
| | Coefficient | p | Coefficient | p | Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | | | |
| KOOS Pain | 1.709 | 0.625 | 0.307 | 0.639 | 1.235 | 0.066 | -8.871 | 0.010 | -8.519 | 0.022 | 7.170 | 0.033 | 96.6 | 481 | 485 |
| | 2.100 | 0.543 | 0.364 | 0.552 | 1.212 | 0.054 | - | - | -9.502 | 0.012 | 3.553 | 0.271 | 96.8 | 520 | 525 |
| | 2.074 | 0.577 | 0.296 | 0.650 | 1.243 | 0.064 | -6.189 | 0.059 | -6.816 | 0.073 | - | - | 96.7 | 490 | 494 |
| | 5.301 | 0.109 | 0.351 | 0.578 | 1.220 | 0.060 | -8.513 | 0.018 | - | - | 5.740 | 0.098 | 96.8 | 506 | 510 |
| | 4.837 | 0.151 | 0.341 | 0.590 | 1.223 | 0.059 | -6.392 | 0.059 | - | - | - | - | 96.8 | 513 | 517 |
| | 2.139 | 0.536 | 0.358 | 0.599 | 1.209 | 0.055 | - | - | -8.457 | 0.020 | - | - | 96.9 | 526 | 530 |
| | 5.603 | 0.098 | 0.402 | 0.499 | 1.196 | 0.050 | - | - | - | - | 1.631 | 0.624 | 97 | 546 | 550 |
| KOOS Symptoms | 1.451 | 0.608 | 0.533 | 0.483 | 1.296 | 0.095 | -4.612 | 0.083 | -8.782 | 0.005 | 7.189 | 0.010 | 93.2 | 478 | 482 |
| | 0.962 | 0.718 | 0.536 | 0.454 | 1.327 | 0.069 | - | - | -9.820 | 0.001 | 4.904 | 0.054 | 93.7 | 514 | 518 |
| | 1.836 | 0.557 | 0.556 | 0.465 | 1.321 | 0.089 | -2.052 | 0.446 | -7.074 | 0.029 | - | - | 93.4 | 489 | 493 |
| | 5.186 | 0.070 | 0.455 | 0.535 | 1.278 | 0.088 | -4.437 | 0.142 | - | - | 5.714 | 0.057 | 93.7 | 506 | 510 |
| | 4.734 | 0.109 | 0.474 | 0.519 | 1.285 | 0.087 | -2.307 | 0.425 | - | - | - | - | 93.8 | 514 | 518 |
| | 1.021 | 0.714 | 0.550 | 0.442 | 1.325 | 0.070 | - | - | -8.380 | 0.005 | - | - | 93.8 | 522 | 526 |
| | 4.591 | 0.104 | 0.459 | 0.508 | 1.304 | 0.066 | - | - | - | - | 2.918 | 0.296 | 94.1 | 544 | 548 |
| KOOS ADL | 0.991 | 0.722 | 0.002 | 0.998 | 0.044 | 0.956 | -7.479 | 0.006 | -7.942 | 0.009 | 5.523 | 0.039 | 92.8 | 479 | 483 |
| | 1.685 | 0.544 | 0.022 | 0.977 | 0.035 | 0.962 | - | - | -8.500 | 0.006 | 2.262 | 0.312 | 93.3 | 519 | 523 |
| | 1.285 | 0.663 | 0.020 | 0.980 | 0.033 | 0.967 | -5.524 | 0.035 | -6.634 | 0.030 | - | - | 92.9 | 488 | 492 |
| | 4.457 | 0.100 | 0.025 | 0.973 | 0.017 | 0.982 | -7.295 | 0.014 | - | - | 4.164 | 0.141 | 93.2 | 506 | 510 |
| | 4.131 | 0.132 | 0.008 | 0.992 | 0.016 | 0.983 | -5.575 | 0.038 | - | - | - | - | 93.3 | 512 | 516 |
| | 1.712 | 0.536 | 0.033 | 0.965 | 0.030 | 0.967 | - | - | -7.732 | 0.009 | - | - | 93.3 | 523 | 528 |
| | 4.891 | 0.079 | 0.003 | 0.997 | 0.043 | 0.952 | - | - | - | - | 0.879 | 0.747 | 93.6 | 545 | 549 |
| KOOS Sports/Recreation | 0.247 | 0.955 | 0.397 | 0.710 | 1.790 | 0.101 | -10.408 | 0.014 | -14.506 | 0.003 | 8.261 | 0.049 | 94.7 | 524 | 528 |
| | 0.552 | 0.897 | 0.341 | 0.733 | 1.793 | 0.080 | - | - | -15.408 | 0.001 | 4.218 | 0.290 | 95.0 | 566 | 570 |
| | 0.183 | 0.968 | 0.421 | 0.694 | 1.802 | 0.099 | -7.490 | 0.066 | -12.548 | 0.010 | - | - | 94.8 | 533 | 537 |
| | 6.099 | 0.167 | 0.288 | 0.780 | 1.759 | 0.095 | -10.121 | 0.035 | - | - | 5.787 | 0.210 | 95.0 | 555 | 559 |
| | 5.639 | 0.203 | 0.306 | 0.767 | 1.759 | 0.095 | -7.993 | 0.073 | - | - | - | - | 95.0 | 561 | 566 |
| | 0.603 | 0.887 | 0.354 | 0.723 | 1.787 | 0.081 | - | - | -14.141 | 0.002 | - | - | 95.0 | 571 | 575 |
| | 6.368 | 0.151 | 0.242 | 0.803 | 1.751 | 0.078 | - | - | - | - | 1.055 | 0.809 | 95.3 | 597 | 602 |
| KOOS QOL | 0.680 | 0.881 | 1.549 | 0.141 | 1.318 | 0.207 | -10.892 | 0.013 | -12.664 | 0.010 | 9.510 | 0.030 | 94.5 | 524 | 528 |
| | 2.023 | 0.648 | 1.351 | 0.175 | 1.575 | 0.116 | - | - | -13.026 | 0.008 | 4.780 | 0.250 | 95.0 | 567 | 571 |
| | 1.173 | 0.809 | 1.529 | 0.146 | 1.338 | 0.201 | -7.526 | 0.078 | -10.405 | 0.038 | - | - | 95.0 | 534 | 578 |
| | 6.048 | 0.171 | 1.576 | 0.120 | 1.364 | 0.176 | -10.591 | 0.028 | - | - | 6.048 | 0.171 | 95.3 | 553 | 557 |
| | 5.456 | 0.225 | 1.558 | 0.124 | 1.369 | 0.175 | -7.855 | 0.082 | - | - | - | - | 95.4 | 560 | 564 |
| | 2.079 | 0.641 | 1.338 | 0.180 | 1.569 | 0.117 | - | - | -11.623 | 0.014 | - | - | 95.1 | 573 | 577 |
| | 6.746 | 0.128 | 1.389 | 0.151 | 1.589 | 0.102 | - | - | - | - | 2.200 | 0.614 | 65.3 | 596 | 600 |

Supplemental Table 2.3. Full Statistical Analyses of KOOS Scores. Highlighted cells indicate best-fit model.

# APPENDIX B

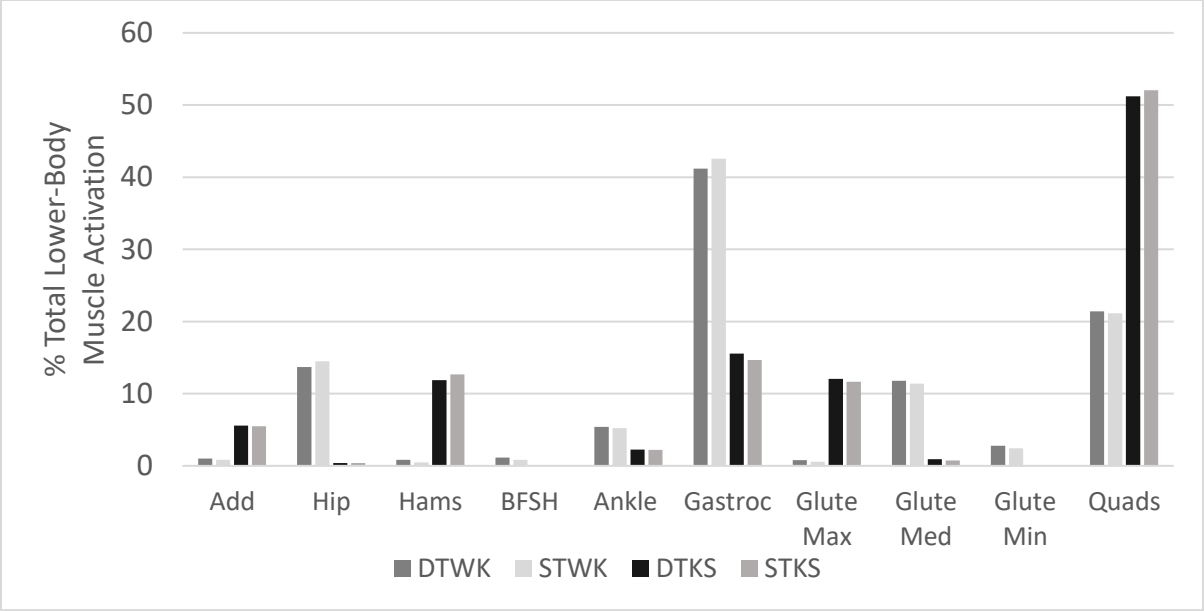
## CHAPTER 3 SUPLLEMENTAL INFORMATION

| **Solve For** | **Target Power** | **Statistical Tests** | **Type I Error Rate** | **Outcomes** |
|---|---|---|---|---|
| Sample Size | 0.8 | Hotelling Lawley Trace | 0.05 | Knee Adduction Moment |
| **Repeated Measures Dimension** | **Type** | **Measurements** | **Clustering** | **Fixed Predictor** |
| Condtion | Categorical | Single Task; Dual Task | N/A | N/A |
| **Hypothesis Choice** | **Within Hypothesis** | **Marginal Means: Single Task** | **Marginal Means: Dual Task** | **Scale Factor** |
| Condition: Main Effect | All Mean Differences Zero | 0.21 | 0.181 | 1 |
| **Variability: KAM** | **Standard Deviation Ratio** | **Repeated Measure Correlation** | **Scale Factor Variance** | |
| 0.09 | 1; 1 | 0.8; 0.8 | 1 | |

Supplemental Table 3.1. Power Analysis Inputs (GLIMMPSE v3.0).

| Model Dependent Variable | Fixed Factors | | | | | | | | Covariates | | | | | | Model Comparison | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Movement Type | | Condition | | Movement Type*Condition | | Sex | | Age | | BMI | | Speed*Movement Type | | Adjusted $R^2$ (%) | AICc | BIC |
| | Coefficient | p | Coefficient | p | Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | Standard Coefficient | p | | | |
| Peak Tibiofemoral Contact Fy | 2.298 | <0.001 | 0.084 | 0.291 | 0.075 | 0.339 | 0.057 | 0.730 | -0.062 | 0.634 | -0.610 | <0.001 | 0.520 | 0.010 | 90.42 | 403.86 | 409.45 |
| | 2.300 | <0.001 | 0.086 | 0.281 | 0.074 | 0.345 | 0.069 | 0.668 | - | - | -0.615 | <0.001 | 0.530 | 0.009 | 90.45 | 401.82 | 407.42 |
| | 2.293 | <0.001 | 0.091 | 0.256 | 0.083 | 0.292 | 0.174 | 0.397 | -0.111 | 0.495 | - | - | 0.574 | 0.006 | 90.84 | 418.07 | 423.68 |
| | 2.299 | <0.001 | 0.083 | 0.301 | 0.073 | 0.348 | - | - | -0.069 | 0.587 | -0.618 | <0.001 | 0.503 | 0.011 | 90.44 | 402.17 | 407.78 |
| | 2.303 | <0.001 | 0.029 | 0.712 | 0.040 | 0.619 | 0.036 | 0.820 | -0.099 | 0.437 | -0.628 | <0.001 | - | - | 89.65 | 409.12 | 414.73 |
| | 2.300 | <0.001 | 0.093 | 0.244 | 0.082 | 0.296 | 0.197 | 0.326 | - | - | - | - | 0.587 | 0.005 | 90.88 | 416.73 | 422.36 |
| | 2.300 | <0.001 | 0.084 | 0.291 | 0.072 | 0.356 | - | - | - | - | -0.625 | <0.001 | 0.511 | 0.010 | 90.46 | 400.15 | 405.77 |
| | 2.305 | <0.001 | 0.030 | 0.702 | 0.037 | 0.641 | 0.019 | 0.902 | - | - | -0.638 | <0.001 | - | - | 89.67 | 407.44 | 413.06 |
| | 2.294 | <0.001 | 0.088 | 0.272 | 0.080 | 0.305 | - | - | -0.135 | 0.401 | - | - | 0.544 | 0.008 | 90.89 | 417.45 | 423.07 |
| | 2.298 | <0.001 | 0.031 | 0.700 | 0.044 | 0.578 | 0.075 | 0.710 | -0.155 | 0.343 | - | - | - | - | 90.15 | 424.52 | 430.15 |
| | 2.303 | <0.001 | 0.030 | 0.710 | 0.040 | 0.619 | - | - | -0.095 | 0.446 | -0.624 | <0.001 | - | - | 89.66 | 407.28 | 412.91 |
| | 2.296 | <0.001 | 0.090 | 0.260 | 0.079 | 0.312 | - | - | - | - | - | - | 0.555 | 0.006 | 90.93 | 416.32 | 421.96 |
| | 2.300 | <0.001 | 0.032 | 0.690 | 0.042 | 0.597 | 0.105 | 0.599 | - | - | - | - | - | - | 90.19 | 423.64 | 429.28 |
| | 2.305 | <0.001 | 0.031 | 0.700 | 0.037 | 0.641 | - | - | - | - | -0.635 | <0.001 | - | - | 89.68 | 405.53 | 411.17 |
| | 2.298 | <0.001 | 0.031 | 0.699 | 0.044 | 0.578 | - | - | -0.164 | 0.304 | - | - | - | - | 90.18 | 423.27 | 428.92 |
| Mediolateral Distance from JC to COPk | 0.0073 | <0.001 | 0.0001 | 0.607 | 0.0002 | 0.052 | 0.0002 | 0.332 | -0.0001 | 0.691 | 0.0009 | <0.001 | 0.0001 | 0.579 | 97.97 | -1273.32 | -1267.78 |
| | 0.0073 | <0.001 | 0.0001 | 0.619 | 0.0002 | 0.052 | 0.0002 | 0.353 | - | - | 0.0009 | <0.001 | 0.0001 | 0.609 | 97.97 | -1288.52 | -1282.91 |
| | 0.0073 | <0.001 | 0.0001 | 0.559 | 0.0002 | 0.060 | 0.0004 | 0.181 | 0.0000 | 0.987 | - | - | 0.0002 | 0.181 | 98.05 | -1271.78 | -1266.17 |
| | 0.0073 | <0.001 | 0.0000 | 0.646 | 0.0001 | 0.717 | - | - | 0.0000 | 0.803 | 0.0009 | <0.001 | 0.0001 | 0.717 | 97.97 | -1287.23 | -1281.62 |
| | 0.0073 | <0.001 | 0.0000 | 0.703 | 0.0002 | 0.038 | 0.0002 | 0.379 | -0.0001 | 0.732 | 0.0009 | <0.00 | - | - | 97.97 | -1287.63 | -1282.02 |
| | 0.0073 | <0.001 | 0.0001 | 0.558 | 0.0002 | 0.060 | 0.0004 | 0.170 | - | - | - | - | 0.0002 | 0.445 | 98.06 | -1286.68 | -1281.05 |
| | 0.0073 | <0.001 | 0.0000 | 0.653 | 0.0002 | 0.048 | - | - | - | - | 0.0001 | <0.001 | 0.0001 | 0.738 | 97.98 | -1302.56 | -1296.94 |
| | 0.0073 | <0.001 | 0.0000 | 0.707 | 0.0002 | 0.039 | 0.0002 | 0.394 | - | - | 0.0009 | <0.001 | - | - | 97.98 | -1302.90 | -1297.27 |
| | 0.0073 | <0.001 | 0.0001 | 0.599 | 0.0002 | 0.055 | - | - | 0.0000 | 0.834 | - | - | 0.0002 | 0.578 | 98.06 | -1284.35 | -1278.72 |
| | 0.0073 | <0.001 | 0.0000 | 0.694 | 0.0002 | 0.041 | 0.0004 | 0.216 | 0.0000 | 0.959 | - | - | - | - | 98.05 | -1285.79 | -1280.16 |
| | 0.0073 | <0.001 | 0.0000 | 0.705 | 0.0002 | 0.038 | - | - | 0.0000 | 0.823 | 0.0001 | <0.001 | - | - | 97.98 | -1301.77 | -1296.15 |
| | 0.0073 | <0.001 | 0.0001 | 0.594 | 0.0002 | 0.054 | - | - | - | - | - | - | 0.0002 | 0.571 | 98.07 | -1299.20 | -1293.56 |
| | 0.0070 | <0.001 | 0.0000 | 0.692 | 0.0000 | 0.041 | 0.0000 | 0.201 | - | - | - | - | - | - | 98.06 | -1300.69 | -1295.05 |
| | 0.0073 | <0.001 | 0.0000 | 0.707 | 0.0002 | 0.038 | - | - | - | - | 0.0009 | <0.001 | - | - | 97.98 | -1317.13 | -1311.49 |
| | 0.0073 | <0.001 | 0.0000 | 0.695 | 0.0002 | 0.040 | - | - | 0.0001 | 0.806 | - | - | - | - | 98.07 | -1298.65 | -1293.01 |

Supplemental Table 3.2. Full Statistical Analyses of Tibiofemoral Contact Forces. Highlighted cells indicate best-fit model.




Supplemental Figure 3.1. Relative Activations of Lower Body Muscle Groups. For each condition, the muscle groups contribution sum to 100%. Abbreviations are as follow: Add: Adductor Muscles. Hip: Miscellaneous Actuators at the Hip. Hams: Hamstrings. BFSH: Bicep Femoral Short Head. Ankle: Miscellaneous Actuators at the Ankle. Glute Max, Med, and Min: Gluteus Maximus, Medius, and Minimus. Quads: Quadricep.