BIOMECHANICAL ADAPTATIONS AFTER FATIGUING EXERCISE IN HEALTHY AND ACL RECONSTRUCTED INDIVIDUALS

A Dissertation

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Doctor of Philosophy

By

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ABSTRACT

Background: Lower extremity injuries, including anterior cruciate ligament (ACL) rupture, are most common in more active and fit individuals. Furthermore, athletes with a history of ACL reconstruction (ACLR) who return to a high level of sport are at increased risk for another ACL injury or graft failure. This suggests that highly fit athletes may be at increased risk for injury and re-injury due to adaptations after exercise modeling demands of sport. The overall purpose of this study was to compare biomechanical adaptations after different exercise protocols, compare adaptations between ACLR and healthy individuals based on fitness level, and predict changes in running gait after exercise using objective measures of strength and functional performance. **Methods:** Thirty-three individuals with history of primary, unilateral, uncomplicated ACLR (22F/11M, 19.9±2.2 years, 68.3±10.9 kg, 170.4±8.4 cm, 22.7±23.3 months post-reconstruction) and 29 healthy individuals (18F/11M, 20.1±1.5 years, 70.0±9.9 kg, 172.7±8.7 cm) were divided into two groups based on maximal oxygen consumption level (higher fitness and lower fitness). Healthy individuals completed two exercise protocols (walking and interval) and ACLR individuals completed only the interval exercise. Lower extremity running biomechanics were captured before and after fatiguing exercise. Sagittal, frontal, and transverse knee, hip, and trunk kinematics and triplanar knee and hip internal moments were calculated for all subjects. Data were reduced to 101 points for 0-100% of the gait cycle for kinematics and reduced to 41 points for 0-40% of the gait cycle (stance phase) for kinetics. Change scores (post – pre) were calculated for each point of the gait cycle with 90% confidence intervals. Significant differences between groups (ACLR, healthy), fitness levels (higher fit, lower fit), and exercise protocols (walking, interval) were determined when 90% confidence intervals did not overlap for three or more consecutive points. All subjects also completed bilateral knee extensor and knee flexor strength testing as well as single hop for distance and a modified square hop task. **Results:** Healthy individuals demonstrated changes predominantly in the sagittal plane after the walking protocol, however the interval protocol resulted in triplanar changes in lower extremity and trunk kinematics and kinetics after exercise. Both the high fit and low fit ACLR maintained sagittal plane kinematics after exercise compared to healthy individuals who increased knee flexion, hip flexion, and had a more extended trunk position. The main variables that predicted limb asymmetry during running gait were quadriceps strength symmetry and the modified square hop test. Quadriceps strength symmetry was correlated with gait asymmetry in subjects with ACLR before exercise, while performance on the modified square hop test was correlated with changes in gait on the involved limb. **Conclusions:** Alterations in movement patterns after exercise are dependent on type of exercise and fitness level. Higher fit individuals with ACLR demonstrated more changes in the sagittal plane after interval exercise while lower fit individuals with ACLR demonstrated increased transverse plane motion during running gait after exercise. Biomechanical adaptations due to fatiguing exercise modeling a sport environment may contribute to increased risk of secondary injury and long-term consequences such as joint degeneration. Knee extensor peak torque symmetry is the most predictive variable for symmetrical vertical ground reaction forces during running, however changes in functional tests may be more appropriate for predicting changes in gait after exercise.

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APPROVAL OF THE DISSERTATION

This dissertation, “Biomechanical Adaptations after Fatiguing Exercise in Healthy and ACL Reconstructed Individuals” has been approved by the Graduate Faculty of the Curry School of Education in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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DEDICATION

This dissertation is dedicated to Axel Ashley, who left the world far too soon after he entered it. We miss you every single day, little man.

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TABLE OF CONTENTS

Manuscript III

SECTION III: APPENDICES

Appendix A: The Problem

Appendix B: Review of Literature

LIST OF TABLES

APPENDIX D

LIST OF FIGURES

APPENDIX D

Section II: Manuscript I

Biomechanical Adaptations During Running Differ Based on Type of Exercise and Fitness Level

ABSTRACT

Neuromuscular fatigue may contribute to lower extremity injury risk due to adaptations that occur after prolonged and strenuous exercise. Lower extremity injuries are most common in those who are most active and are more fit, suggesting that adaptations may differ depending on the type of exercise and fitness level of the athlete. The purpose of this study was to compare changes in running gait in highly fit and recreationally active individuals before and after two exercise protocols. **Methods:** Twenty-four healthy individuals (19.7±0.9 years, 172.8±9.1cm, 70.5±10.2kg) divided into higher fitness (n = 13) and lower fitness (n = 11) groups each completed two different exercise protocols (walking and interval) for 30 minutes. Lower extremity running biomechanics were captured before and after exercise. Sagittal, frontal, and transverse knee, hip, and trunk kinematics and triplanar knee and hip internal moments were measured on the dominant leg. Data were reduced to 101 points for 0-100% of the gait cycle for kinematics and reduced to 41 points for 0-40% of the gait cycle (stance phase) for kinetics. Change scores (post – pre) were calculated for each point of the gait cycle with 90% confidence intervals. Significant differences between exercise protocols were determined when 90% confidence intervals did not overlap for three or more consecutive points. **Results:** There were significant differences in trunk flexion (-2.62°), lateral trunk flexion (-1.22°), and hip rotation moment (Range: -0.17 Nm/kg, 0.14 Nm/kg) between fitness levels after the walking exercise. After the interval exercise, there were differences between fitness levels in knee flexion (Range: - 7.04°, -5.08°), knee abduction (Range: -5.48°, -1.45°), knee rotation (Range: -3.04°, 1.90°), hip flexion (4.06°), hip abduction (3.17°), hip rotation (Range: -3.24°, -2.38°), trunk flexion (Range: -3.12°, -2.92°), trunk lateral flexion (1.40°), and trunk rotation (-2.73°). There were also differences in knee flexion moment (Range: -0.32 Nm/kg, -0.08 Nm/kg), knee abduction moment (Range: -0.18 Nm/kg, 0.04 Nm/kg), knee rotation moment (Range: -0.12 Nm/kg, -0.05 Nm/kg), hip flexion moment (Range: -0.19 Nm/kg, 0.24 Nm/kg), hip abduction moment (Range: -0.12 Nm/kg, 0.26 Nm/kg), and hip rotation moment (Range: -0.18 Nm/kg, -0.17 Nm/kg).

Conclusion: Alterations in movement patterns after exercise are dependent on type of exercise and fitness level. It is important to consider both type of exercise and fitness level when assessing altered movement patterns in response to prolonged and fatiguing exercise.

INTRODUCTION

Over 80% of all musculoskeletal injuries are from participation in recreational physical activity or sport, with injuries to the lower extremity accounting for 60% of all musculoskeletal injuries.[43] Injuries to the lower extremity are most common in more fit and physically active individuals,[43] with injury risk increasing for high-level athletes.[9] Neuromuscular fatigue has been theorized a contributing factor associated with lower extremity musculoskeletal injury in athletes because injuries are most common at the end of games.[24,25] In order to better understand the neuromuscular effects of fatigue, the effects of exercise on movement patterns during functional tasks has been well-studied, however exercise protocols used to induce experimental fatigue vary widely in the published literature.[5]

Several laboratory-based exercise protocols exist, some induce fatigue using controlled and isolated repetitive movements until task failure.[55,75] There is some advantage to isolating muscle fatigue with controlled, uni-planar exercises but generalization to sport environments is limited.[55] Other exercise protocols utilize a combination of anaerobic exercises, such as squat jumps and short sprints, or single leg landings and squats.[15,59] These protocols result in fatigue using exercises that simulate movements experienced during sport and activity, however do not incorporate the aerobic component of prolonged sport participation. Graded treadmill exercise has been used previously to test cardiopulmonary fitness[92] and is commonly used to induce neuromuscular fatigue.[17,73] Fatiguing exercise protocols that challenge both anaerobic and aerobic systems and simulate the demands of sports may be best suited for assessing fatigue-related biomechanical adaptations that are more generalizable to highly active athletes participating in prolonged and intense sport environments.

Along with type of exercise, demands of exercise required to illicit fatigue may differ based on fitness level. Fatigue is often defined as a decline in force or power production.[26] High level athletes have increased strength compared to recreational athletes,[31,64] and may require different sport-specific demands to evaluate fatigue-related biomechanical adaptations that may increase risk for injury in more fit athletes.[42,43] Therefore, the purpose of this study was to compare changes in running gait before and after generic exercise and sport-specific exercise between different fitness levels.

METHODS

This was a descriptive laboratory study with a repeated measures design. The independent variables in this study were exercise (2 levels: walking and interval exercise), time (2 levels: pre-exercise and post-exercise), and fitness (2 levels: higher fit and lower fit). The dependent variables included sagittal, frontal, and transverse plane knee, hip, and trunk kinematics and internal knee and hip moments normalized to mass (Nm/kg).

Subjects

Twenty-four healthy individuals (15 females, 9 males, 19.7±0.9 years, 172.8±9.1cm, 70.5±10.2kg) without history of lower extremity, trunk injury or surgery within the previous 12 months volunteered to participate in this study. Subjects were divided based on fitness level into a higher fit and lower fit group based on the group median for maximal oxygen uptake during aerobic exercise (Table 1). All subjects provided written informed consent approved by the university's institutional review board for health sciences research.

Instrumentation

Maximal oxygen uptake (VO_2max) was collected using a metabolic cart (Vmax Encore Metabolic Cart, Becton, Dickinson and Company, Franklin Lakes, NJ). Flow, volume, and gas concentrations were calibrated before each test. A heart rate monitor (Polar T31 Transmitter, Polar Electro Inc., Lake Success, NY) was fitted below the pectoral muscles during metabolic testing and the exercise protocols. A 6-20 Borg Scale was used for rating of perceived exertion (RPE) during metabolic testing and the exercise protocols.[10] A 12-camera motion capture system (Vicon Motion Systems, Ltd, UK; SEM = 0.75-2.3 degrees) and a split-belt instrumented treadmill (Bertec, Columbus, OH) were used to collect kinematic and kinetic data during running. Kinematic data were sampled at 250Hz and ground reaction forces were sampled at 1000Hz. Data were synchronized, exported, and filtered using a zero-lag fourth-order Butterworth filter at 14.5Hz using MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL). The FITLIGHT Trainer™ reactive light system (FITLIGHT Sports Corp., Aurora, Ontario) was used during the exercise session.

Procedures

Subjects reported to the laboratory for three sessions separated by at least 48 hours. All subjects completed the Godin Leisure-Time Exercise Questionnaire[33] and the Marx Activity Scale.[62] The first session included an incremental treadmill test to determine VO_2max. The second and third sessions both included assessment of running biomechanics before and after 30 minutes of exercise and in counterbalanced order.

VO_2max Testing

Initial treadmill velocity was a comfortable running velocity for each individual subject and velocity was increased by 0.22m/s (0.5 mph) every 2 minutes (the duration of each stage) until volitional fatigue. Heart rate and RPE were recorded at the end of every stage and at volitional fatigue. VO_2max data were averaged every 60 seconds and normalized to body mass. The highest mL/kg/min value was recorded as the subject's VO_2max and was confirmed based on either a respiratory exchange ratio greater than 1.15 or RPE $\geq$ 17.[33]

Gait Analysis

For both sessions, subjects wore their own athletic shoes appropriate for running, shorts, and a t-shirt. Eight clusters of retro-reflective markers were attached to the thorax, sacrum, bilaterally over the lateral mid-thigh, lateral mid-calf, and forefoot for the entire collection.[14] The medial and lateral malleoli, medial and lateral knee joint lines, L5, T12, C7, and bilateral anterior superior iliac spine were digitized to identify joint centers. All subjects walked and ran on the treadmill for five minutes to acclimate to the treadmill and reflective clusters. Twelve capture periods of 2-seconds each were collected for each subject during running at 3.33 m/s (7.5mph) before and after exercise.

Exercise Protocols

The walking exercise session included five repeated cycles of treadmill walking at 1.34m/s (3.0mph) for 5 minutes immediately followed by 1 minute of jumping exercises (repeated bouts of 10 squat jumps and 10 lateral hops). The treadmill incline increased by 0.5°/min during walking phases and stopped increasing at 8.5° (15%) incline.[62] The interval exercise session included five repeated cycles of treadmill walk, jog, and run intervals and one minute of agility exercises using a reactive light system. Each 5-minute treadmill interval included 15 seconds of walking at 1.34m/s (3.0 mph), 25 seconds of jogging at 2.68m/s (6.0 mph), and 20 seconds of running at 3.33m/s (7.5 mph). The velocities and durations of intervals were designed based on global positioning system data collected from a men's collegiate soccer team during matches over an entire season (unpublished data) to mimic a sport environment. Eight reactive lights were set up in a semi-circle, each positioned 3.5 meters from the subject and illuminated in a random order. The subject was instructed to run to touch the illuminated light as quickly as possible and backpedal to the starting position when another light illuminated. Subjects were instructed to touch as many lights as possible in one minute and encouragement was provided to ensure maximal effort. Heart rate and RPE were recorded during the final 15 seconds of each treadmill bout for both exercise protocols and immediately after exercise completion (Figure 1).

Data Processing and Statistical Analyses

Kinematic data were reduced to 101 points to represent 0-100% of the gait cycle (heel strike to ipsilateral heel strike). Heel strike was defined as the point when vertical ground reaction forces exceeded 20 N.[93] Kinetic data were reduced to 41 points to represent 0-40% of the gait cycle from heel strike to toe off (when vertical ground reaction forces were less than 20 N) to represent the stance phase of running gait. All internal moments were normalized to body mass (Nm/kg). Means and 90% confidence intervals of knee, hip, and trunk sagittal, frontal, and transverse plane kinematics and knee and hip triplanar kinetics for the dominant limb were calculated for each 1% of the gait cycle before and after exercise. Dominant limb was defined as the preferred kicking leg.[62] Kinematics and kinetics were presented as a change score by subtracting the pre-exercise value from the post-exercise value and compared between fitness levels after walking exercise and interval exercise. Mean differences and associated pooled standard deviations were calculated for periods of the gait cycle when confidence intervals for change scores did not overlap for three or more consecutive points.[33] Mean differences and pooled standard deviations were calculated to compare the magnitude of difference between fitness levels.

Post-exercise heart rate and RPE between fitness levels and exercise protocols were compared using an analysis of variance. Significance level was set *a priori* at $P \leq 0.05$ and all analyses were run in SPSS (version 22.0, Chicago, IL).

RESULTS

The interval exercise resulted in a significantly higher post-exercise heart rate compared to the walking exercise (Interval = 189.1±10.5bpm, Walking = 180.9±12.9bpm, $P < 0.0001$), however there was no difference in RPE (Interval = 17.7±1.5, Walking = 16.6±1.9, $P = 0.256$). There was no difference in HR ($P = 0.477$) or RPE ($P = 0.186$) between fitness levels in either the walking or interval exercise.

Walking Exercise

There were no significant differences between higher and lower fit healthy individuals after the walking exercise in knee or hip kinematics (Figure 2). The higher fit group demonstrated increased trunk extension during late stance through early swing (2.6±0.51°) compared to the lower fit group after walking exercise, however the lower fit group demonstrated increased trunk lateral flexion towards the ipsilateral side during early stance (1.22±0.19°) and midstance (1.38±0.11°) compared to the higher fit group (Figure 2, Table 2).

The lower fit group demonstrated increased internal hip extension moment during loading response (0.08±0.02 Nm/kg) and midstance (0.17±0.02 Nm/kg) and increased internal hip flexion moment later in midstance (0.14±0.01 Nm/kg) after walking exercise compared to the higher fit group (Figure 3, Table 2). There were no other significant differences in kinetics between fitness levels.

Interval Exercise

The higher fit group demonstrated increased knee extension during stance phase (5.08±1.20°) and increased knee flexion during swing phase (7.04±1.08°) compared to the lower fit group after interval exercise (Figure 4, Table 3). The higher fit group also exhibited increased knee valgus during late stance phase (1.45±0.37°) and swing phase (5.48±1.37°) compared to the lower fit group after interval exercise (Figure 4, Table 3) as well as increased knee external rotation during midstance (3.04°±0.08°). The lower fit group demonstrated increased knee external rotation during late stance phase (1.87±0.04°) compared to the higher fit group after interval exercise (Figure 4, Table 3).

The lower fit group also demonstrated increased hip extension from terminal stance through swing phase (4.06±0.85°), hip abduction during swing phase (3.17±0.29°), and hip internal rotation during early stance phase (3.24±0.44°) and late stance phase (2.38±0.55°) compared to the higher fit group after interval exercise (Figure 4, Table 3). The higher fit group exhibited increased trunk extension during stance (2.92±0.61°) and swing phase (3.12±0.58°) compared to the lower fit group after interval exercise, however the lower fit group demonstrated increased trunk lateral flexion towards the contralateral side during swing phase (1.40±0.30°) and increase trunk rotation towards the ipsilateral side during swing phase (2.73±0.95°) (Figure 4, Table 3).

The higher fit group demonstrated increased internal knee flexion moment during midstance (0.32±0.09 Nm/kg) and at terminal stance (0.08±0.01 Nm/kg) compared to the lower fit group after interval exercise (Figure 5, Table 3). The higher fit group also demonstrated increased internal knee varus moment during early stance (0.15±0.05 Nm/kg) and midstance (0.18±0.02 Nm/kg) and increased internal knee valgus moment during terminal stance (0.04±0.02 Nm/kg) compared to the lower fit group after interval exercise (Figure 5, Table 3). After interval exercise, the higher fit group also demonstrated increased internal knee internal rotation moment during early stance (0.08±0.02 Nm/kg), midstance (0.12±0.02 Nm/kg), and late stance phase (0.05±0.01

Nm/kg) compared to the lower fit group. The higher fit group demonstrated increased internal hip flexion moment during early stance phase (0.19±0.05 Nm/kg) and late stance (0.15±0.03 Nm/kg), however the lower fit group exhibited increased internal hip flexion moment during midstance (0.13±0.02 Nm/kg) and terminal stance (0.24±0.04 Nm/kg) after interval exercise (Figure 5, Table 3). The higher fit group demonstrated increased internal hip abduction moment during early stance (0.26±0.09 Nm/kg) while the lower fit group demonstrated increased internal hip abduction moment during terminal stance (0.12±0.03 Nm/kg) after interval exercise. The lower fit group also demonstrated increased internal knee external rotation moment during early stance (0.17±0.03 Nm/kg) and midstance (0.18±0.03 Nm/kg) compared the higher fit group after interval exercise.

DISCUSSION

The results of this study indicate that biomechanical adaptations after fatiguing exercise are different based on type of exercise and fitness level. Both the higher and lower fit groups demonstrated differences in running gait after each type of exercise. Both groups displayed changes predominantly in the sagittal plane after the walking protocol, which has been seen previously in a healthy population after graded treadmill exercise.[53] In contrast to the walking exercise, both groups demonstrated triplanar changes in lower extremity and trunk kinematics and kinetics after the interval exercise. The interval exercise was designed to mimic sport demands and elicited a significantly higher HR compared to the walking protocol. This suggests that fatiguing exercise that models sport is more demanding than generic exercise and results in triplanar biomechanical adaptations that may be associated with injury risk.

After interval exercise, the higher fit group exhibited less sagittal plane motion in the dominant leg during stance phase of gait. Decreased knee flexion along with less trunk flexion during stance phase has been hypothesized as an adaptation to increase running economy[11,49] during the propulsion phase of gait after fatiguing exercise. Decreased joint motion, as observed in the current study may be interpreted as increase stiffness during running, and may allow for increased efficiency of movement. Lower extremity muscle stiffness has been associated with increased running economy suggesting that more fit individuals may increase stiffness in the lower extremity joints to assist with more powerful toe-off for efficiency.[23] Abdominal activation also increases during gait after exercise,[14] which may contribute to decreased trunk flexion during gait. Abdominal musculature endurance should therefore be a consideration along with lower extremity alignment when evaluating injury risk in higher fit individuals. However decreased trunk flexion may also displace the center of mass posteriorly. This change helps to explain the observation of increased internal knee flexion moment in higher fit individuals after exercise due to a more posteriorly oriented ground reaction force in the sagittal plane.

In the current study, we observed decreased sagittal plane knee joint motion combined with increased knee valgus and external rotation at the time of toe-off in the higher fit group after exercise. This combination of movements has been associated with increased risk of knee injury.[39,45] Fewer frontal and transverse plane adaptations were present after the walking exercise, supporting that neuromuscular fatigue from exercise mimicking sport may increase risk for injury. In the current study, we observed exercise-related adaptations started at the knee during early stance phase and at more proximal joints during swing phase of running gait. This suggests that changes in knee kinematics may precede compensation patterns at the trunk during gait. The relationship between these observations is an area for future research. However, altered knee kinematics has been shown to increase trunk power absorption,[84] which may lead to increased strain on the spinal and abdominal musculature to stabilize movements when fatigued. Back pain is a frequent complaint for high-level athletes.[27] The role of distal fatigue-related biomechanical adaptations in athletes is an area of further study.

In the current study, subjects in the lower fit group had a similar response to the higher fit group after the walking exercise, however responded very differently to the interval exercise. The lower fit group demonstrated increased knee flexion during stance phase after exercise. Subjects in the current study ran at a set velocity while measuring pre-post exercise biomechanics. The findings of the current study suggest that individuals with lower aerobic fitness may have increased stride length to adapt to running at a set velocity, which may have been a challenging or novel running speed. Increased stride length has been associated with altered kinematics.[18,29] These lower fit subjects may have been running at a greater relative percentage of their own maximal velocity and exhibited a different strategy to increase movement economy after 30 minutes of exercise compared to the higher fit subjects. The lower fit group increased knee flexion angle, which may increase force attenuated at the knee musculature when fatigued rather than using more proximal muscle groups, leading to increased overuse injuries, such as patellofemoral pain, in recreational athletes.[20] These adaptive movement patterns and reliance on knee musculature may also lead to muscular imbalances. Patients with patellofemoral pain often demonstrate decreased hip strength.[68] Lack of proximal joint strength may be related to reduced hip force attenuation when fatigued compared to a high fit individual.

There were a few limitations in the current study. Fatigue was not quantified, however RPE was around the threshold for volitional fatigue during maximal oxygen uptake testing[40] and HR was similar to those reported after a soccer match (Table 1).[60] Reflective markers were also placed on the subject at the beginning of the session were not removed for exercise. This was a study design decision to ensure we were able to capture running gait immediately after the completion of the exercise protocol rather than delay post-testing. The markers were secured with tape to reduce likelihood of movement.

CONCLUSIONS

Alterations in movement patterns after exercise are dependent on type of exercise and fitness level. There were fewer and lower magnitude changes in gait mechanics after the walking exercise, however the interval exercise resulted in more prominent and longer duration movement pattern alterations in both higher and lower fit individuals. Higher fit individuals demonstrated increased knee extension, hip extension, knee valgus, and trunk movement after exercise mimicking sport demand, which may be in an effort to increase running economy when fatigued. The lower fit group demonstrated a more knee-dominant strategy to attenuate forces when fatigued which may lead to different pathologies, such as patellofemoral pain. Therefore, it is important to consider both type of exercise and fitness level when assessing altered movement patterns after exercise.

Table 1. Subject demographics for higher fit and lower fit groups with standard deviations.

	High Fit (N = 13)	Low Fit (N = 11)	P-value
Sex (M/F)	(6M/7F)	(3M/8F)	--
Age (yrs)	19.8 (0.9)	19.5 (0.9)	0.42
Height (cm)	174.3 (11.1)	171.1 (6.1)	0.37
Mass (kg)	70.9 (9.9)	70.0 (11.0)	0.84
Godin Leisure-Time	127.6 (48.1)	112.8 (27.9)	0.36
Marx Activity	11.3 (4.1)	8.8 (5.2)	0.21
Heart Rate (bpm)	186.2 (11.2)	184.0 (13.4)	0.54
VO2max (mL/kg/min)	56.1 (4.7)	46.6 (2.9)	<0.0001

Table 2. Mean differences and pooled standard deviations for portions of gait where change scores between the higher fit and lower fit groups were significantly different after walking exercise. A negative value indicates that the lower fit group had greater flexion, adduction, or internal rotation compared to the higher fit group. Kinematics are presented in degrees and kinetics are moments normalized to body mass (Nm/kg).

Variable	Gait Cycle	Mean Difference (Standard Deviation)
Trunk Flexion	25-57%	-2.62 (0.51)
Lateral Trunk Flexion	0-9%	-1.22 (0.19)
	19-33%	-1.38 (0.11)
Hip Flexion Moment	1-3%	-0.08 (0.02)
	17-19%	-0.17 (0.02)
	22-25%	0.14 (0.01)

Table 3. Mean differences and pooled standard deviations for portions of gait where change scores between the higher fit and lower fit groups were significantly different after interval exercise. A negative value indicates that the lower fit group had greater flexion, adduction, or internal rotation compared to the higher fit group. Kinematics are presented in degrees and kinetics are moments normalized to body mass (Nm/kg).

	Variable	Gait Cycle	Mean Difference (Standard Deviation)
KNEE	Knee Flexion	0-30%	-5.08 (1.20)
		37-70%	7.04 (1.08)
	Knee Adduction	27-35%	-1.45 (0.37)
		64-83%	-5.48 (1.37)
	Knee Rotation	24-27%	-3.04 (0.08)
		35-37%	1.90 (0.04)
HIP	Hip Flexion	37-78%	4.06 (0.85)
	Hip Adduction	69-80%	3.17 (0.29)
	Hip Rotation	4-11%	-3.24 (0.44)
		29-38%	-2.38 (0.55)
TRUNK	Trunk Flexion	18-32%	-2.92 (0.61)
		68-84%	-3.12 (0.58)
	Lateral Trunk Flexion	61-89%	1.40 (0.30)
	Trunk Rotation	46-87%	-2.73 (0.95)
KNEE	Knee Flexion Moment	15-35%	-0.32(0.09)
		38-40%	-0.08(0.01)
	Knee Adduction Moment	3-7%	-0.15(0.05)
		20-24%	-0.18(0.02)
		35-40%	0.04(0.02)
	Knee Rotation Moment	8-11%	-0.08(0.02)
		14-26%	-0.12(0.02)
		29-31%	-0.05(0.01)
HIP	Hip Flexion Moment	5-9%	-0.19(0.05)
		23-28%	0.13(0.02)
		30-33%	-0.15(0.03)
		38-40%	0.24(0.04)
	Hip Adduction Moment	2-7%	0.26(0.09)
		35-40%	-0.12(0.03)
	Hip Rotation Moment	4-11%	-0.17(0.03)
		20-24%	-0.18(0.03)

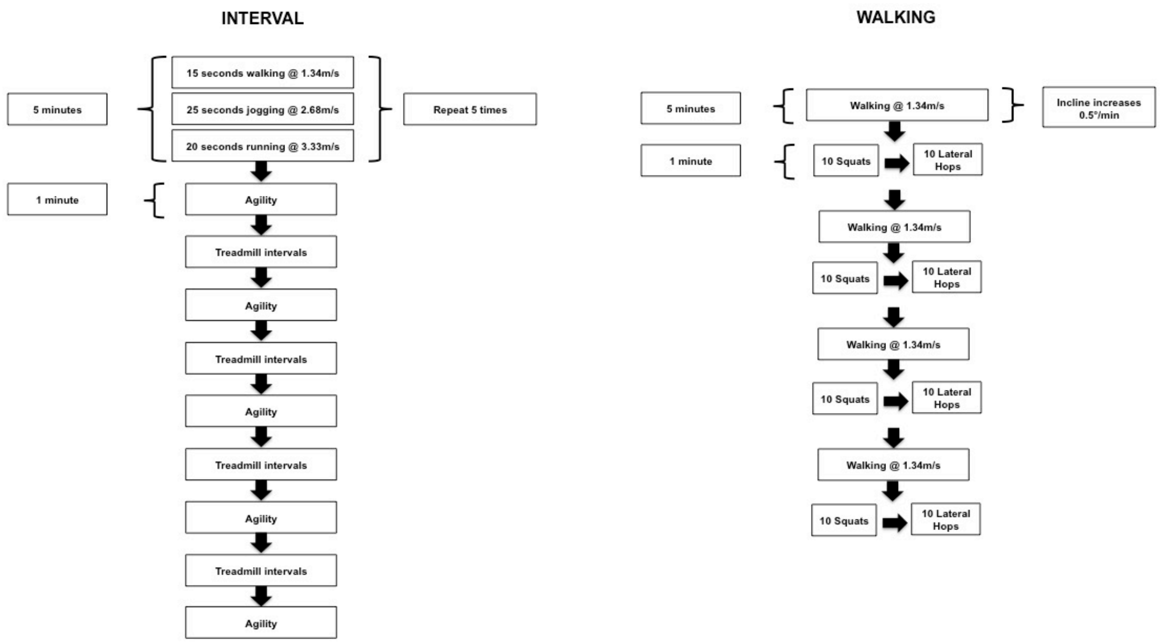

Figure 1. Progression of the interval and walking protocols. Both protocols included five minutes of treadmill exercise mixed with one minute of agility for five sets (30 minutes of exercise).

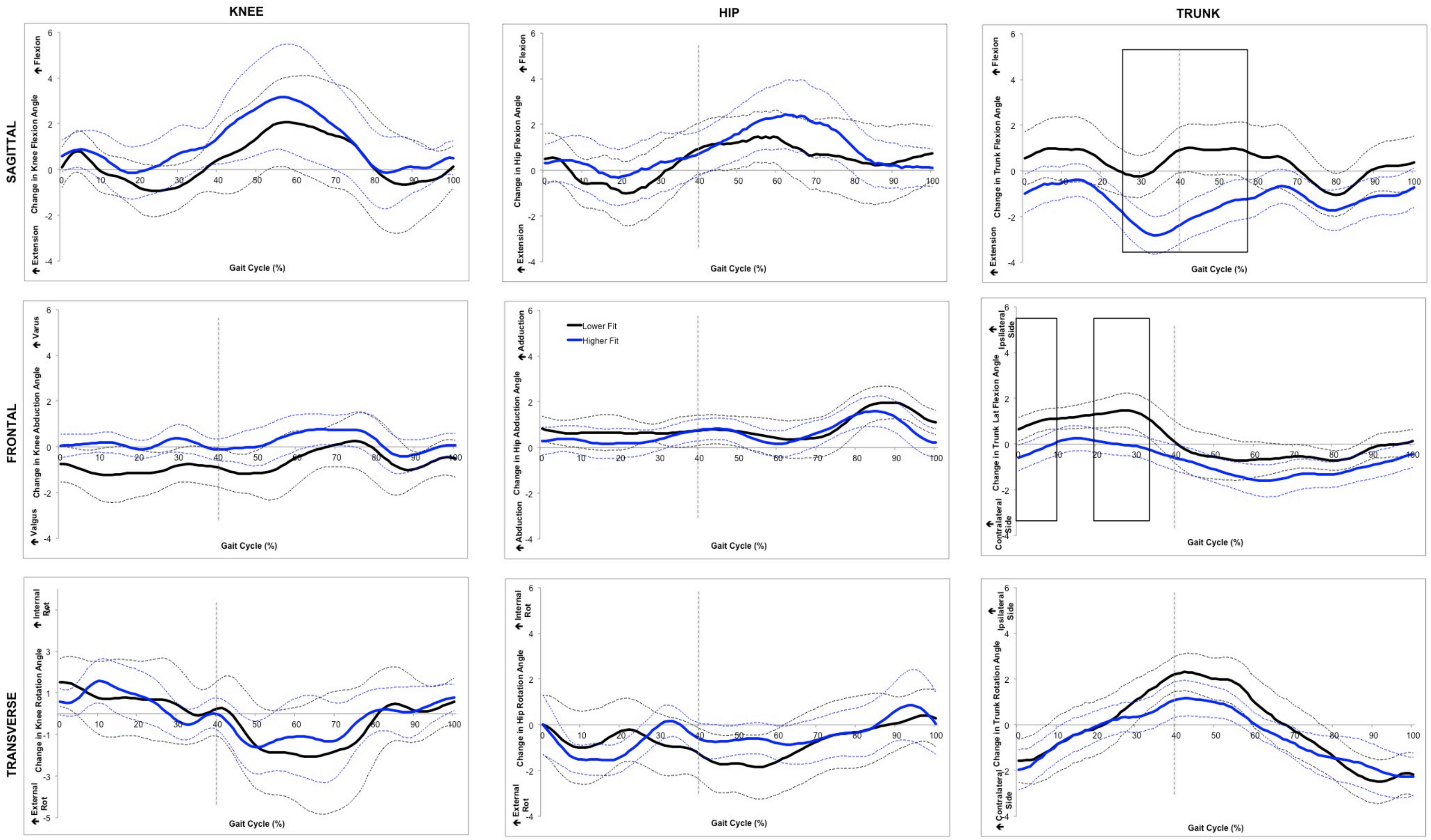

Figure 2. Differences in changes in kinematics (degrees) after the walking exercise between the higher fit group (blue) and the lower fit group (black) with 90% confidence intervals over the entire gait cycle (0-100%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered significantly different.

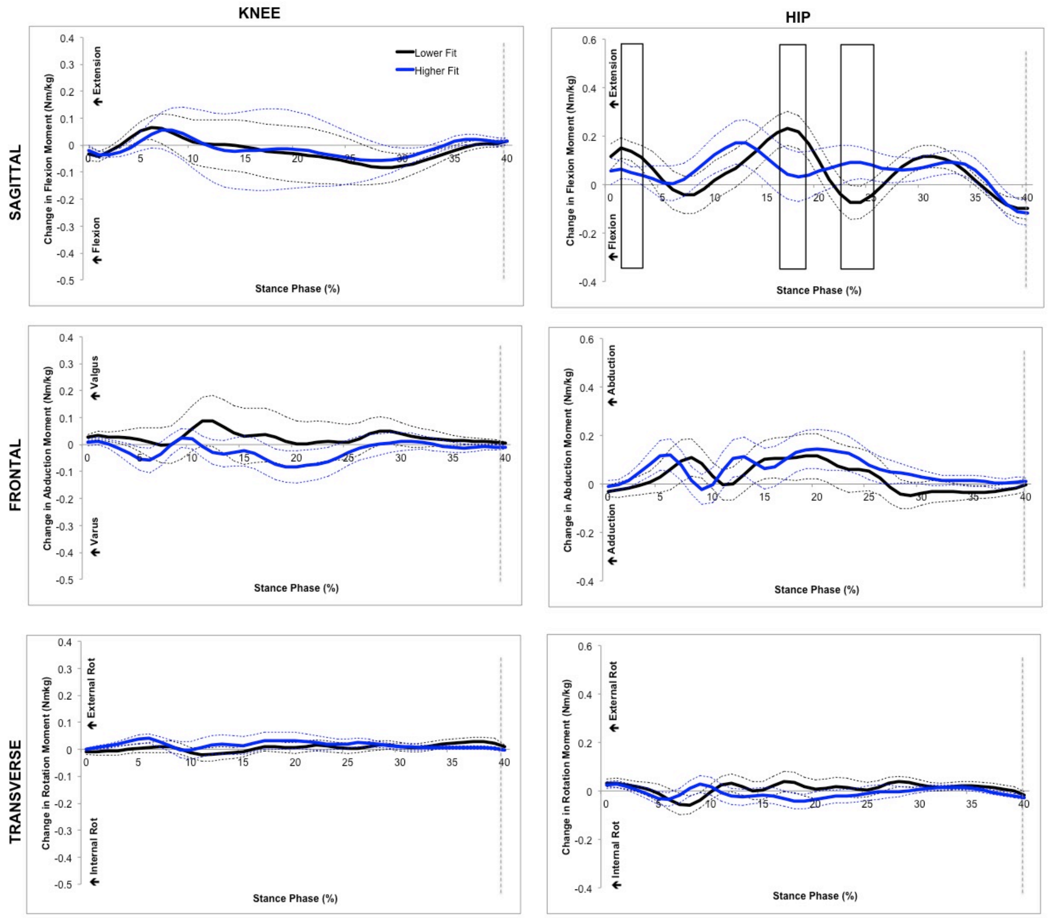

Figure 3. Differences in changes in kinetics (Nm/kg) after the walking exercise between the higher fit group (blue) and the lower fit group (black) with 90% confidence intervals over the entire stance phase of gait (0-40%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered significantly different.

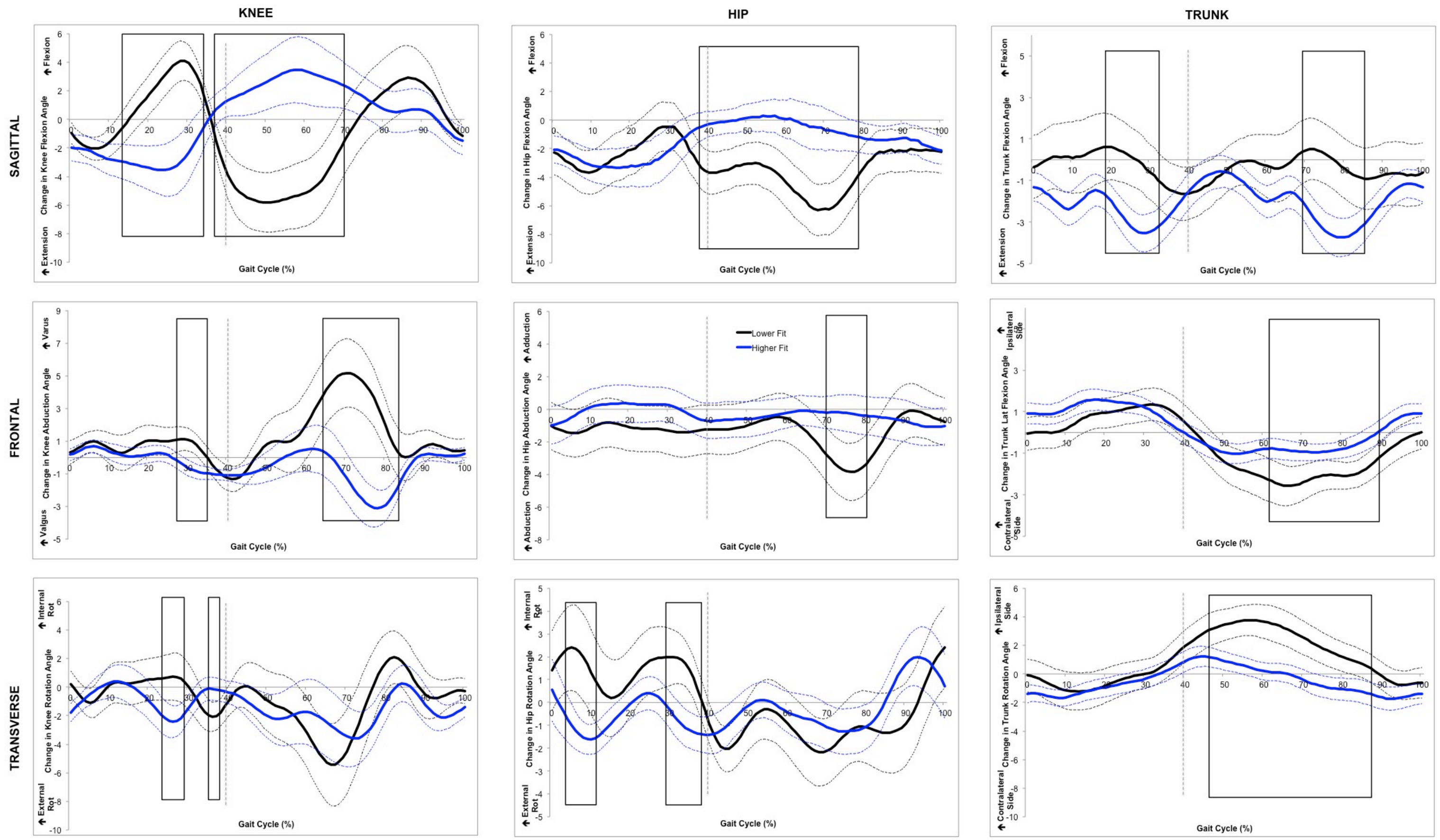

Figure 4. Differences in changes in kinematics (degrees) after the interval exercise between the higher fit group (blue) and the lower fit group (black) with 90% confidence intervals over the entire gait cycle (0-100%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered significantly different.

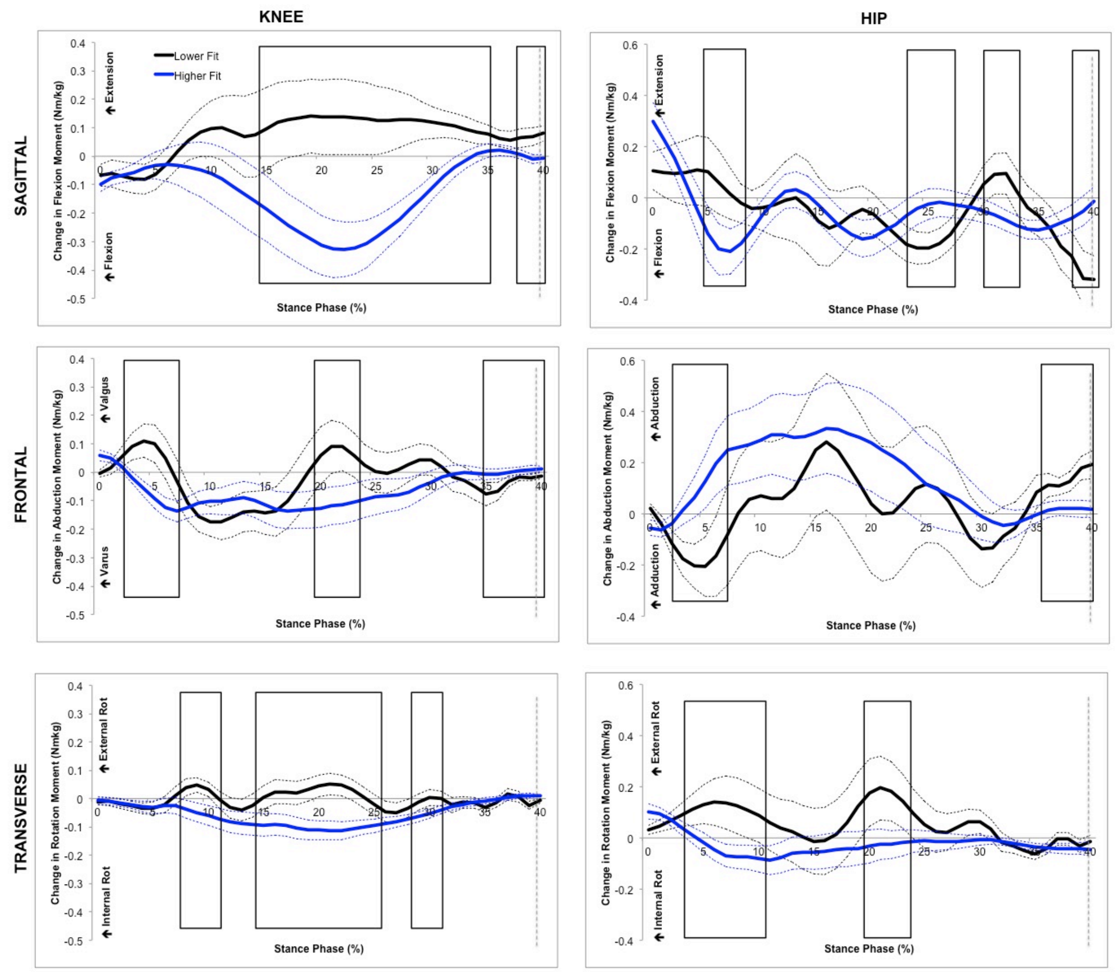

Figure 5. Differences in changes in kinetics (Nm/kg) after the interval exercise between the higher fit group (blue) and the lower fit group (black) with 90% confidence intervals over the entire stance phase of gait (0-40%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered significantly different.

Section II: Manuscript II

Biomechanical Adaptations During Running After Exercise in Healthy and ACL Reconstructed Individuals

ABSTRACT

Athletes with history of anterior cruciate ligament reconstruction (ACLR) who return to high level of sport are at increased risk of another ACL injury or graft failure. Neuromuscular fatigue during sport may result in adaptive movement patterns that increase risk of injury in patients with ACLR. The purpose of this study was to compare changes in an ACLR limb and a healthy control limb based on fitness level before and after fatiguing exercise. **Methods:** Thirty-three individuals with history of primary, unilateral, uncomplicated ACLR (22F/11M, 19.9±2.2 years, 68.3±10.9 kg, 170.4±8.4 cm, 22.7±23.3 months) and 29 healthy individuals (18F/11M, 20.1±1.5 years, 70.0±9.9 kg, 172.7±8.7 cm) were divided into two groups based on maximal oxygen consumption level (higher fitness and lower fitness). Lower extremity biomechanics were captured before and after exercise. Sagittal, frontal, and transverse knee, hip, and trunk kinematics and triplanar knee and hip internal moments were measured on the dominant leg. Data were reduced to 101 points for 0-100% of the gait cycle for kinematics and reduced to 41 points for 0-40% of the gait cycle (stance phase) for kinetics. Change scores (post – pre) were calculated for each 1% with 90% confidence intervals. Significant differences between exercise protocols were determined when 90% confidence intervals did not overlap for three or more consecutive points. Mean differences and pooled standard deviations were calculated for all significant differences during the gait cycle. **Results:** High fit individuals with ACLR demonstrated decreased knee flexion (Range: -3.13°, -1.54°) and hip flexion (Range: -2.14°, -1.77°), and increased knee abduction (Range: -2.79°, -2.62°) compared to high fit healthy individuals after exercise. High fit individuals with ACLR also demonstrated increased knee flexion moment (-0.18±0.04 Nm/kg) and hip extension moment (0.10±0.03 Nm/kg) compared to high fit healthy individuals after exercise. Low fit individuals with ACLR demonstrated decreased knee flexion (-2.88±0.35°), increased hip adduction (1.48±0.22°), increased knee external rotation (Range: -4.45°, -2.86°), increased hip external rotation (Range: -2.87°, -2.82°), and increased trunk rotation (3.61±1.77°) compared to low fit healthy individuals after exercise. Low fit individuals with ACLR also exhibit increased knee internal rotation moment (Range: -0.04, -0.03 Nm/kg) and hip internal rotation moment (Range: -0.07, -0.04 Nm/kg) after exercise compared to low fit healthy individuals. **Conclusions:** High fit individuals demonstrated more changes in the sagittal plane while low fit individuals demonstrated increased transverse plane motion during running gait after exercise. Biomechanical adaptations due to fatiguing exercise modeling a sport environment may contribute to increased risk of secondary injury and long-term consequences such as joint degeneration.

INTRODUCTION

Anterior cruciate ligament (ACL) tears are common in recreational and competitive athletics with an annual incidence of about 69 isolated ACL tears per 100,000 person-years.[81] After ACL injury, many patients opt to undergo ACL reconstruction (ACLR) surgery to return to activity, however are still at increased risk for secondary injury. Up to 25% of athletes under 25 years old who return to a high level of sport have a subsequent ACL injury either to ipsilateral or contralateral limb.[91] These high-level athletes are more likely to incur a second injury during a game[51] after being returned to sport.[3,32] This suggests that neuromuscular fatigue from sport demands may be a contributing factor to subsequent ACL injuries in these high-level athletes.

The most commonly used objective measurements to determine readiness to return to activity after ACLR include quadriceps strength and hopping performance.[48,91] The single-leg hop test is one of the most popular tests for assessing functional performance,[35] however the hop test is unable to predict injury and is not able to track meaningful gains in function as time from surgery increases.[71,79] Therefore, return to play decision-making should include a number of other factors other than just patient-reported outcomes and laboratory measures of functional outcomes.[36] These measures should include sport-specific outcomes[16] as well as appreciation for sport risk modifiers and decision modifiers. The missing variable that is not currently accounted for in decision models for return-to-play is biomechanical and muscular adaptations after exercise that models a sport environment. Appreciation for changes in functional movement after exercise may provide valuable information that guides safe return to activity after ACLR.

Running and sprinting comprise more than half of all soccer games,[90] indicating that high-speed gait should be evaluated after ACLR. Decreased knee flexion and knee extension moment are evident during walking gait in patients with ACLR up to three years post-surgery.[85] Patients with ACLR also demonstrate increased lateral trunk flexion towards the ipsilateral side, forward trunk lean, increased knee external rotation and knee adduction during jogging compared to healthy controls.[69,87] Jogging gait is further altered after graded treadmill exercise in patients with ACLR, demonstrating decreased hip flexion and increased knee flexion moment compared to healthy subjects.[53] These changes in gait combined with fatigue-resistant quadriceps after ACLR,[13,86] support that individuals with ACLR demonstrate different gait adaptations after exercise compared to healthy individuals. However the applicability of graded treadmill exercise to sport environments may be limited. There is no current study evaluating high-speed running mechanics in patients with ACLR after sport-specific exercise. Furthermore, most studies combine all patients with ACLR regardless of fitness level. It is unclear if a higher and lower fit individual responds to exercise differently after ACLR. Differences in adaptations based on fitness level may guide return to activity decisions. Therefore, the purpose of this study was to compare changes during high-speed running gait in individuals with ACLR and healthy controls after exercise mimicking sport based on fitness level.

METHODS

This was a descriptive laboratory study with a case-control repeated measures design. The independent variables in this study were group (2 levels: ACL and healthy control), and fitness (2 levels: high fit and low fit). The dependent variables included sagittal, frontal, and transverse plane knee, hip, and trunk kinematics and sagittal, frontal, and transverse knee and hip internal moments normalized to mass (Nm/kg). Dependent variables also included heart rate and rate of perceived exertion (RPE).

Subjects

Thirty-three individuals with history of primary, unilateral, uncomplicated ACLR (22 Females/11 Males, 19.9±2.2 years, 68.3±10.9 kg, 170.4±8.4 cm, 22.7±23.3 months post-surgery, 14 Hamstring Grafts/18 Bone-Patellar Tendon Bone Grafts/1 Allograft) and

29 healthy individuals (18 Females/11Males, 20.1±1.5 years, 70.0±9.9 kg, 172.7±8.7 cm) without history of lower extremity injury or surgery in the previous 12 months volunteered to participate in this study. ACLR subjects were divided into two groups based on fitness level (high fit and low fit) using the median of maximal oxygen uptake. Healthy subjects were matched to ACLR based on sex, mass, height, and fitness level. Subject demographics are presented in Table 1. All subjects provided written informed consent approved by our University's institutional review board for health sciences research.

Instrumentation

Maximal oxygen uptake (VO_2max) was collected using a metabolic cart (Vmax Encore Metabolic Cart, Becton, Dickinson and Company, Franklin Lakes, NJ). Flow, volume, and gas concentrations were calibrated before each test. Metabolic data were averaged every 60 seconds and normalized to body mass. A heart rate monitor (Polar T31 Transmitter, Polar Electro Inc., Lake Success, NY) was used to record heart rate during metabolic testing and the exercise protocol along with the 6-20 Borg Scale for rating of perceived exertion (RPE) during metabolic testing and the exercise protocols.[10] A 12-camera motion capture system (Vicon Motion Systems, Ltd, UK; SEM = 0.75-2.3

degrees) and a split-belt instrumented treadmill (Bertec, Columbus, OH) were used to collect kinematic and kinetic data during running. Data were synchronized and exported using MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL). Kinematic data were sampled at 250Hz and ground reaction forces were sampled at 1000Hz. All data were filtered using a zero-lag fourth-order Butterworth filter at 14.5Hz. Internal moments were normalized to body mass (Nm/kg). The FITLIGHT Trainer™ reactive light system (FITLIGHT Sports Corp., Aurora, Ontario) was used for agility exercise during the exercise session.

Procedures

Subjects reported to the laboratory for two sessions, VO_2max testing and the exercise session, separated by at least 48 hours. All subjects completed the Marx Activity Scale,[62] International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC)[4] and the Knee Injury and Osteoarthritis Outcome Score (KOOS).[80]

VO_2max Testing

Initial treadmill velocity was set at a comfortable running pace for each individual and the velocity increased by 0.22m/s (0.5mph) every 2 minutes (the duration of each stage) until volitional fatigue. Metabolic data were collected throughout the treadmill test and heart rate and RPE were recorded at the end of every stage and at volitional fatigue. The highest mL/kg/min value was recorded as the subject's VO_2max and was confirmed based on either a respiratory exchange ratio greater than 1.15 or RPE ≥ 17.[40]

Gait Analysis

The second session included 30 minutes of exercise. Subjects wore their own athletic shoes appropriate for running, shorts, and a t-shirt. Eight clusters of reflective markers were attached to the thorax, sacrum, bilaterally over the lateral mid-thigh, lateral mid-calf, and forefoot for the entire collection.[14] The medial and lateral malleoli, medial and lateral knee joint lines, L5/S1, T12/L1, C7/T1, and bilateral anterior superior iliac spine were digitized to identify joint centers. After calibrating the system and digitizing the skeleton, the subject walked and ran on the treadmill for five minutes to acclimate to the testing equipment. Following five minutes of warm up and familiarization on the treadmill, twelve capture periods of 2-seconds each were collected for each subject during running at 3.33m/s (7.5mph) before exercise and immediately after exercise.

Exercise Session

The exercise protocol lasted for 30 minutes and included five minutes of treadmill walk, jog, and run intervals and one minute of agility using the reactive light system. The five minutes of treadmill intervals included 15 seconds of walking at 1.34m/s (3.0mph), 25 seconds of jogging at 2.68m/s (6.0mph), and 20 seconds of running at 3.33m/s (7.5mph) (Figure 1). The velocities and durations of intervals were designed based on global positioning system data collected from a men's collegiate soccer team during matches over an entire season to mimic a sport environment (unpublished data). The walk, jog, and run intervals were repeated five times for a total of five minutes of treadmill exercise. Eight reactive lights were set up in a semi-circle, with each light positioned 3.5 meters from the subject and illuminated in a random order (Figure 1). The subject was instructed to move as quickly as possible to touch the illuminated light and backpedal to the starting position when another light illuminated. Subjects were instructed to touch as many lights as possible in one minute and encouragement was provided to ensure maximal effort. Heart rate and RPE were recorded during the final 15 seconds of each treadmill bout and immediately after exercise completion.[14]

Data Processing

Kinematic data were reduced to 101 points to represent 0-100% of the gait cycle (heel strike to ipsilateral heel strike). Heel strike was defined as the point when vertical ground reaction forces exceeded 20N.[93] Kinetic data were reduced to 41 points to represent 0-40% of the gait cycle from heel strike to toe off (when vertical ground reaction forces were less than 20N) to represent the stance phase of running gait. All internal moments were normalized to body mass (Nm/kg).

Statistical Analyses

Means and 90% confidence intervals of knee, hip, and trunk sagittal, frontal, and transverse plane kinematics and knee and hip sagittal, frontal, and transverse kinetics for the reconstructed limb in the ACLR group and the nondominant limb in the healthy control group were calculated for each 1% of the gait cycle. Kinematics and kinetics were presented as a change score by subtracting the pre-exercise value from the post-exercise value with 90% confidence intervals. Significant differences between groups (ACLR and healthy) were defined as portions where confidence intervals did not overlap for three or more consecutive points of the gait cycle.[44,53] Mean differences and 90% confidence intervals were calculated to compare the magnitude of difference between groups.

Heart rate and RPE after exercise as well as height, weight, age, and VO_2max were compared between groups and fitness level using a MANOVA. A Pearson's Chi-Square was used to compare graft types between fitness groups. Significant level was set *a priori* at $P \leq 0.05$ and all analyses were run in SPSS (version 22.0, Chicago, IL).

RESULTS

There were no significant differences in age, height, weight, or VO_2max between groups ($P = .093 – 0.899$; Table 1). The only significant difference between fitness levels was VO_2max ($P < 0.0001$; Table 1). The ACLR group had a significantly higher RPE after exercise compared to the healthy group (ACLR = 18.7±1.4, Healthy = 17.6±1.5; $P = 0.007$), however there was no difference in final heart rate between groups (ACLR = 194.0±9.5bpm, Healthy = 189.3±9.9bpm; $P = 0.067$). There were also no differences between fitness levels in heart rate (High fit = 191.5±9.4bpm, Low fit = 192.1±10.6bpm; $P = 0.954$), RPE (High fit = 17.8±1.6, Low fit = 18.6±1.4; $P = 0.066$), or interaction between group and fitness level ($P = 0.475 – 0.921$). There was no difference between ACL fitness groups in graft type ($P = 0.551$).

ACLR vs. Healthy*: Kinematics*

Individuals with ACLR demonstrated decreased knee flexion during running gait after exercise from 29-37% (-1.16±0.18°) and 74-85% (-1.80±0.09°) of the gait cycle compared to healthy limbs after exercise (Figure 2). ACLR limbs demonstrated decreased hip flexion compared to healthy limbs from 26-38% (-1.30±0.25°) and 77-85% (-1.28±0.16°) as well as decreased trunk extension from 9-17% (0.97±0.14°) of the gait cycle compared to healthy limbs (Figure 2). Individuals with ACLR demonstrated increased knee valgus from 0-57% (-1.78±0.50°) and 66-95% (-2.12±1.15°) and decreased hip adduction from 7-24% (-0.87±0.13°) of gait after exercise compared to healthy limbs (Figure 3). ACLR individuals also had increased lateral trunk flexion towards the contralateral side compared to healthy limbs from 0-5% (-0.66±0.05°) and 28-76% (-0.99±1.04°) during gait after exercise (Figure 3). Individuals with ACLR demonstrated increased external rotation at the knee from 30-37% (-0.91±0.10°) and 55-84% (-2.37±0.79°) of gait, at the hip from 0-88% (-2.02±0.73°) and 91-100% (-1.38±0.32°) of gait, and increased trunk rotation towards the ipsilateral side from 17-64% (1.35±1.01°) of gait compared to healthy limbs after exercise (Figure 4).

ACLR vs. Healthy: *Kinetics*

Individuals with ACLR demonstrated decreased knee extension moment from 10-16% (-0.10±0.02 Nm/kg) along with decreased hip extension moment from 21-27% (-0.11±0.04 Nm/kg), increased hip extension moment from 30-35% (0.12±0.06 Nm/kg). After exercise, individuals with ACLR had increased knee abduction moment from 6-21% (0.13±0.03 Nm/kg) and 24-32% (0.09±0.04 Nm/kg), increased hip adduction moment from 32-34% (-0.05±0.01 Nm/kg) of the gait cycle after exercise compared to healthy limbs (Figures 5-6). Individuals with ACLR also exhibited increased knee internal rotation moment from 5-30% (-0.06±0.01 Nm/kg) and 32-36% (0.02±0.00 Nm/kg), increased hip external rotation moment from 9-18% (0.06±0.02 Nm/kg) and 31-34% (0.02±0.01 Nm/kg) and increased hip internal rotation moment from 36-40% (-0.03±0.01 Nm/kg) of gait compared to healthy individuals after exercise (Figures 5-6).

High Fit ACLR vs. High Fit Healthy*: Kinematics*

After exercise, high fit ACLR demonstrated decreased knee flexion from 35-39% (-1.54±0.10°) and 58-80% (-3.13±0.26°), decreased hip flexion from 33-46% (-1.77±0.22°) and 67-84% (-2.14±0.22°), and increased trunk flexion from 23-37% (1.59±0.25°) of gait compared to high fit healthy individuals after exercise (Figure 2).

High fit individuals with ACLR demonstrated increased knee abduction from 0-57% (-2.62±0.53°) and 59-92% (-2.79±1.10°) of gait along with decreased lateral trunk flexion towards the ipsilateral side from 0-3% (-0.79±0.02°) and decreased lateral trunk flexion towards the contralateral side from 46-53% (0.71±0.04°) of the gait cycle compared to high fit healthy individuals (Figure 3). High fit ACLR demonstrated increased external rotation at the hip from 14-34% (-1.89±0.38°) and 61-97% (-2.42±0.72°) and increased trunk rotation towards the contralateral side from 0-29% (-1.46±0.61°) and 71-85% (-1.24±0.48°) of the gait cycle compared to high fit healthy individuals after exercise (Figure 4).

High Fit ACLR vs. High Fit Healthy: *Kinetics*

High fit individuals with ACLR demonstrated increased knee flexion moment from 15-18% (-0.18±0.04 Nm/kg), increased hip flexion moment from 20-28% (-0.21±0.06 Nm/kg), and increased hip extension moment from 32-35% (0.10±0.03 Nm/kg) of gait cycle compared to high fit healthy individuals (Figures 5-6). High fit ACLR also had increased hip abduction moment from 36-40% (0.04±0.04 Nm/kg) compared to high fit healthy individuals after exercise (Figure 6). After exercise, high fit individuals with ACLR also demonstrated increased knee external rotation moment from

0-2% (0.02±0.01 Nm/kg) and increased knee internal rotation moment from 6-29% (-0.09±0.02 Nm/kg) and 37-39% (-0.03±0.01 Nm/kg) of gait along with increased hip external rotation from 6-27% (0.12±0.04 Nm/kg) and increased hip internal rotation from 36-39% (-0.04±0.01 Nm/kg) of gait cycle compared to high fit healthy individuals (Figures 5-6).

Low Fit ACLR vs. Low Fit Healthy*: Kinematics*

Low fit individuals with ACLR demonstrated decreased knee flexion from 22-33% (-2.88±0.35°) and decreased knee extension from 44-63% (3.65±0.42°) of gait cycle compared to low fit healthy individuals after exercise (Figure 2). After exercise, low fit individuals with ACLR also have decreased knee varus from 76-89% (-2.13±1.07°), increased hip adduction from 33-57% (1.48±0.22°), and increased lateral trunk flexion towards the contralateral side from 18-73% (-2.01±1.36°) of gait compared to low fit healthy limbs (Figure 3). Low fit individuals with ACLR demonstrated increased external rotation at the knee from 22-40% (-2.86±0.85°), 50-62% (-3.57±1.31°), and 71-89% (-4.45±1.56°) of gait along with increased external rotation at the hip from 6-12% (-2.82±0.72°), 14-41% (-2.87±0.72°), and 44-61% (-2.84±0.74°) of gait compared to low fit healthy individuals after exercise (Figure 4). Low fit individuals with ACLR also had increased trunk rotation towards the ipsilateral side from 11-66% (3.61±1.77°) of gait after exercise compared to low fit healthy individuals (Figure 4).

Low Fit ACLR vs. Low Fit Healthy: *Kinetics*

Low fit individuals with ACLR demonstrated decreased hip flexion moment from 29-34% (0.18±0.07 Nm/kg) and increased hip flexion moment from 37-39% (-0.11±0.03 Nm/kg) of gait cycle after exercise (Figure 6). Low fit ACLR also had increased knee abduction moment (0.04±0.02 Nm/kg) and decreased hip abduction moment from 36-40% (-0.11±0.05 Nm/kg) of gait compared to low fit healthy individuals after exercise (Figures 5-6). Low fit individuals with ACLR had increased knee internal rotation moment from 0-3% (-0.03±0.01 Nm/kg) and 26-28% (-0.04±0.00 Nm/kg) as well as increased hip internal rotation moment from 38-40% (-0.04±0.01 Nm/kg) of gait cycle compared to low fit healthy individuals (Figures 5-6). External rotation moment at the knee increased from 33-40% (0.03±0.01 Nm/kg) and at the hip from 31-36% (0.04±0.02 Nm/kg) of gait while hip external rotation moment decreased from 24-28% (-0.07±0.01 Nm/kg) of gait in low fit individuals with ACLR compared to low fit healthy individuals after exercise (Figures 5-6).

DISCUSSION

The purpose of this study was to compare kinematic and kinetic changes during high-speed running gait after exercise in ACLR and healthy individuals based on fitness level. Both the high fit and low fit ACLR maintained sagittal plane kinematics after exercise compared to healthy individuals who increased knee flexion, hip flexion, and had a more extended trunk position (Figure 2). The lack of change in sagittal plane mechanics during running in ACLR patients compared to matched healthy individuals may be an effort to preserve quadriceps strength during prolonged and fatiguing exercise. Increased knee flexion during stance phase of running gait requires more eccentric control in the knee extensors, however patients with ACLR often exhibit decreased quadriceps strength.[82,94] Decreased knee extensor strength may be related to a greater reliance on type I, fatigue-resistant muscle fibers during voluntary muscle contractions over the course of exercise.[52,74] The knee extensors are predominantly comprised of power producing type II muscle fibers, which are the first to atrophy after injury.[7] A high level athlete has increased strength compared to a recreational athlete,[31] which is likely due to increased size of type II fibers.[54] Greater atrophy of these muscle fibers after ACLR may contribute to differences in biomechanical adaptations observed in the current study.

In the current study, higher fit subjects with ACLR demonstrated increased knee flexion moment during midstance of running gait. Decreased sagittal plane motion after ACLR has often been associated with quadriceps avoidance, however may also be associated with increased hamstring activation. Hamstring co-contraction decreases anterior tibial translation and internal rotation at the knee[8,30] and may be an adaptation to stabilize the knee after ACLR. Biceps femoris activation shows an upward trend in activation from third minute to tenth minute during high-intensity running after ACLR[77] and may continue to increase in activation as duration of exercise increases. Increased hamstring activation may be coupled with increased triceps surae stiffness[23] to increase running economy when fatigued. Hip and trunk extension after exercise in high fit individuals with ACLR may be to increase running economy rather than avoid force attenuation at the quadriceps.

In contrast to the high fit ACLR group, no difference in knee flexor moment was noted for the low fit group, however there were changes in transverse plane knee motion. This shift towards a more externally rotated knee position has been noted previously during running gait after ACLR,[87] however the low fit ACLR group also demonstrated increased hip external rotation and trunk rotation during stance phase. Increased transverse plane motion in the low fit group may be due to increased step length. Greater pelvic rotation increases stride length and may be a compensatory pattern to fatigue without increasing hip flexion.[57] Increased stride length is associated with increased impact shock,[19,63] which must be attenuated at the joint when the knee is extended. Increased shock attenuation at the knee and hip joint during loading phase of running gait may increase risk of microtrauma and joint pain in these individuals with lower fitness.

The low fit ACLR group also demonstrated increased lateral trunk flexion and increased hip adduction after exercise compared to the healthy group in the current study. These movement patterns have been seen previously in patients with patellofemoral pain,[67] making it unclear if altered frontal plane mechanics follow knee injury or cause anterior knee pain. A healthy individual increases trunk stiffness through increased abdominal activation and decreased trunk motion during gait after exercise.[14] Increased trunk and hip motion in the low fit ACLR after exercise may indicate decreased abdominal strength. More research is needed on abdominal strength in patients with ACLR.

It is concerning that gait patterns in high fit ACLR were largely unchanged after exercise because it indicates that any altered movement patterns that were present before exercise remain after exercise. These high fit individuals are the patients who return back to sport and are at increased risk of developing early onset post-traumatic osteoarthritis.[58,89] Changes in running gait, such as decreased knee flexion and increased knee external rotation,[70,87] modifies lower extremity loading patterns and cartilage loading patterns which increase incidence of OA.[34] High fit healthy individuals demonstrated changes in gait after exercise, such as increased knee flexion, decreasing the stiffness of the system and increasing loading at the knee extensors. Consistent loading of cartilage, even when fatigued, may contribute to the progression of OA in high-level athletes with ACLR who demonstrate a preservation pattern.[53]

There were a few limitations in the current study. Reflective markers were placed on the subject at the beginning of the session and were not removed during exercise. This was a study design decision to ensure running gait was collected immediately after exercise rather than delay post-testing to replace reflective markers. The markers were all secured with tape to reduce likelihood of movement. Another limitation was that fatigue was not quantified using a biomarker, but was assumed based on RPE and HR. Average RPE after exercise was above the threshold for volitional fatigue[40] on the incremental treadmill test. Lastly, the ACLR group had a wide range of time since surgery, included a range of surgical techniques, and included both males and females. The purpose of this study was to compare groups based on fitness level rather than time from surgery and future studies should focus on both time from surgery and fitness level. Although we did not control for surgical technique, the group in this study represents the percentage of autograft and allograft reconstructions used in the clinic. In a typical clinic, about 45% of reconstructions use patellar tendon, 36% use hamstring graft, and 19% use an allograft.[48] Proportions of graft types in this study were reflective of a typical clinic. Both males and females were included in this study to best represent all patients who have reconstructions and return back to activity, regardless of sex. Healthy individuals were also matched to subjects with ACLR based on sex to minimize sex differences, however future investigations should separate by both fitness level and sex to determine if there are further adaptive patterns after exercise based on sex.

CONCLUSIONS

Changes in running gait after exercise are dependent on fitness level. High fit and low fit individuals have different adaptations to exercise, with high fit ACLR largely preserving movement patterns in sagittal, frontal, and transverse planes while low fit ACLR increased frontal and transverse plane movement during running gait. Biomechanical adaptations may increase risk of secondary injury and long-term consequences such as OA, suggesting that fitness level should be a consideration when making return to activity decisions after reconstruction.

Table 1. Means and standard deviations for subject demographics.

	All Subjects		High Fit		Low Fit	
	ACLR (N = 33)	Healthy (N = 29)	ACLR (N = 17)	Healthy (N = 17)	ACLR (N = 16)	Healthy (N = 12)
Age (years)	19.9 (2.2)	20.1 (1.5)	20.3 (2.3)	20.4 (1.8)	19.6 (2.2)	19.6 (0.8)
Sex (F/M)	22F/11M	18F/11M	8F/9M	8F/9M	14F/2M	10F/2M
Height (cm)	170.4 (8.4)	172.7 (8.7)	171.3 (8.7)	174.6 (9.7)	169.4 (8.3)	170.1 (6.6)
Mass (kg)	68.3 (10.9)	70.0 (9.9)	68.1 (9.5)	70.7 (9.2)	68.4 (12.5)	68.9 (11.1)
VO_2max (mL/kg/min)	50.8 (6.8)	54.1 (9.3)	56.2 (4.1)	59.3 (8.7)	45.0 (3.3)	46.7 (2.8)
Marx	12.0 (4.0)	10.5 (4.4)	12.9 (3.1)	11.7 (3.7)	11.0 (4.7)	8.8 (4.9)
$IKDC_{0-100}$	87.7 (9.8)	98.2 (2.2)	90.2 (7.5)	98.6 (2.1)	85.0 (11.4)	97.6 (2.4)
$KOOS_{0-100}$	92.4 (6.5)	99.5 (0.9)	93.0 (5.2)	99.5 (1.0)	91.7 (7.8)	99.5 (0.8)
Graft Type	14 HG/18 PT/1 A		7 HG/10 PT		7 HG/8 PT/1 A	
Time Post-Surgery (months)	22.7 (23.3)	--	22.3 (22.5)	--	23.1 (24.8)	--

Abbreviations: HG = hamstring graft; PT = patellar tendon graft; A = Allograft

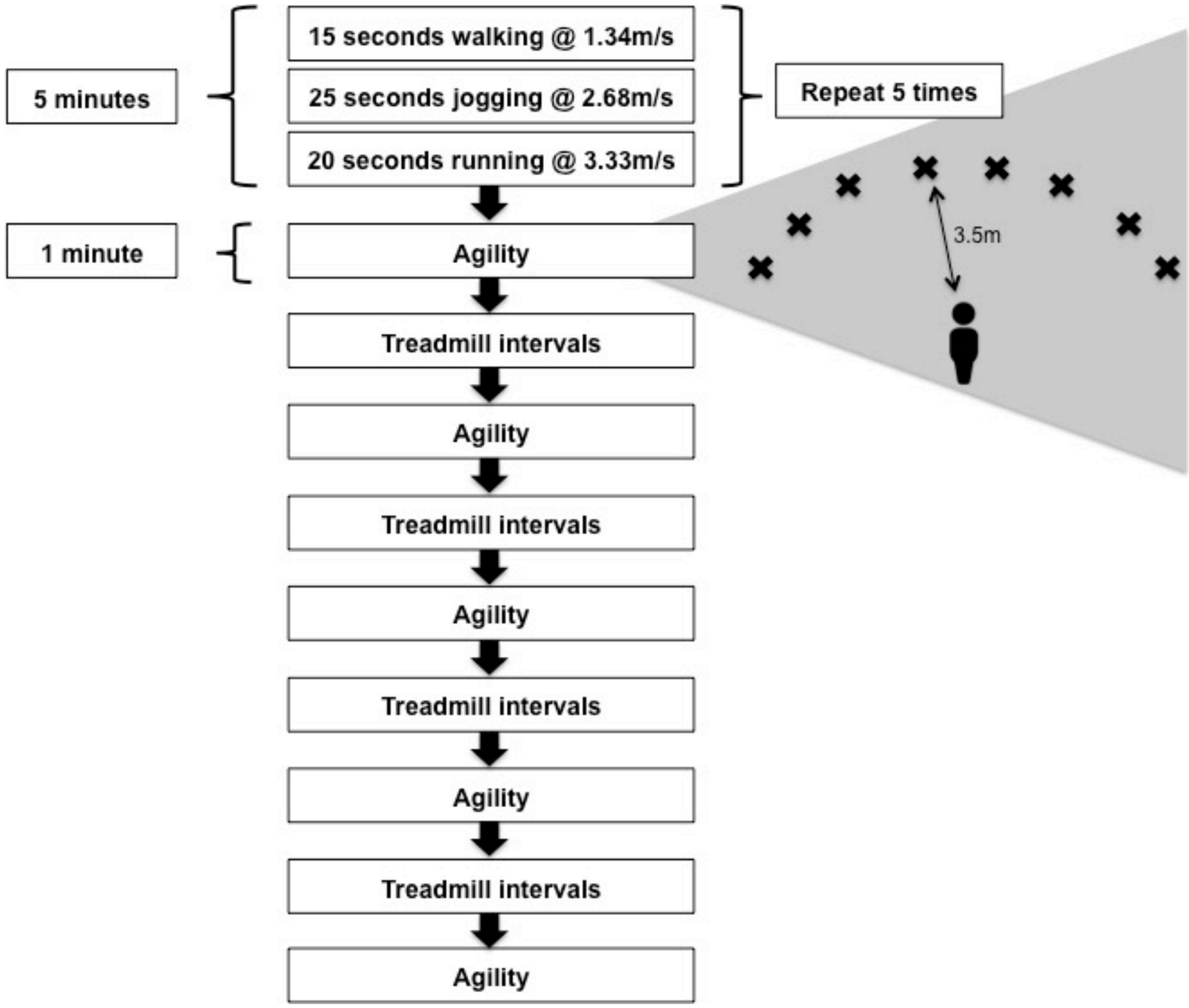

Figure 1. Progression of the exercise protocol used in this study. The protocol included five sets of five minutes of treadmill intervals with one minute of agility for a total of 30 minutes of exercise.

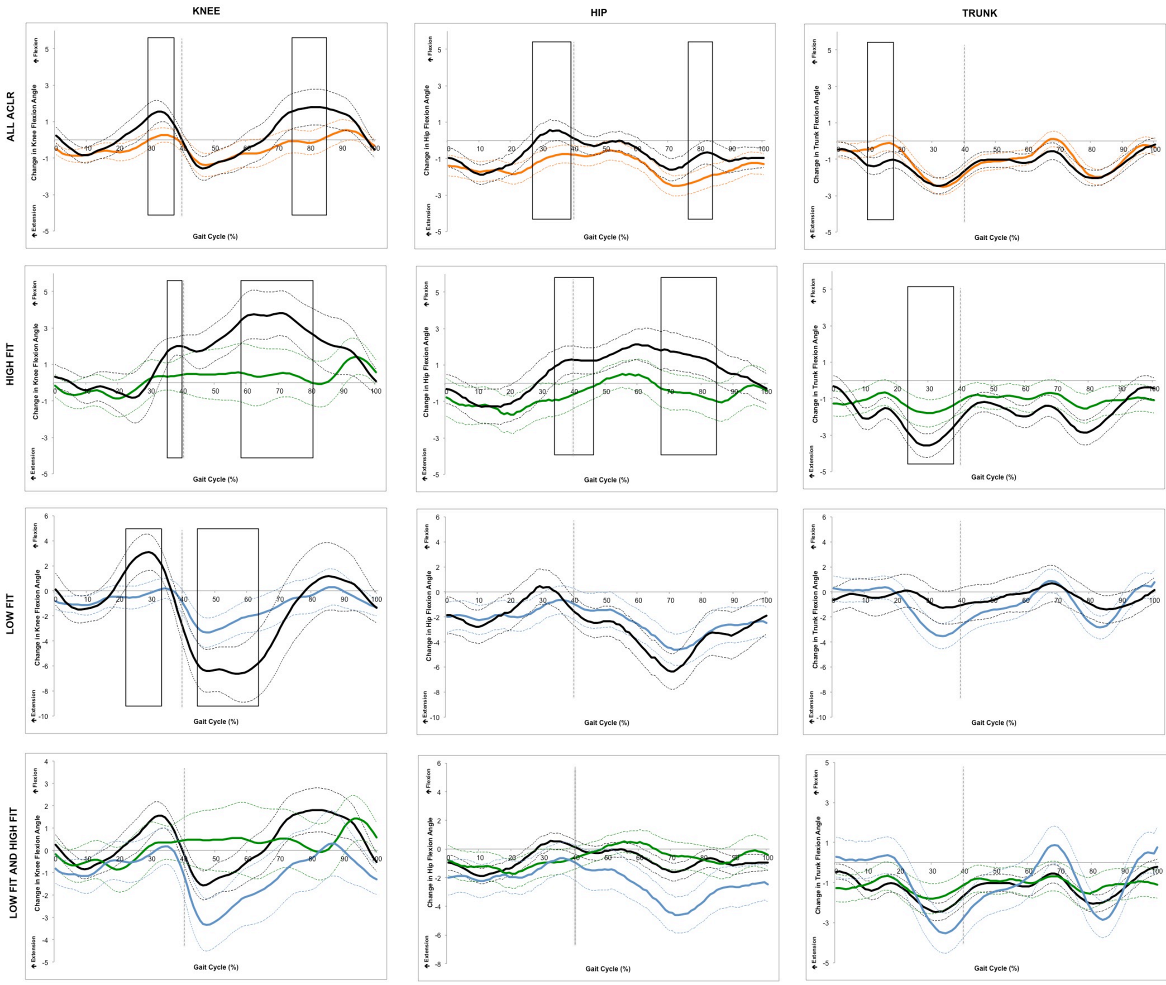

Figure 2. Mean change (degrees) in sagittal knee, hip, and trunk kinematics after exercise over the gait cycle in all ACLR and all healthy, high fit ACLR and high fit healthy, and low fit ACLR and low fit healthy. Areas where 90% confidence intervals did not overlap for three or more consecutive points were considered statistically significant. The orange line represents all ACLR, the green line represents high fit ACLR, and the blue line represents low fit ACLR. The black line represents healthy. The vertical dashed line represents toe-off.

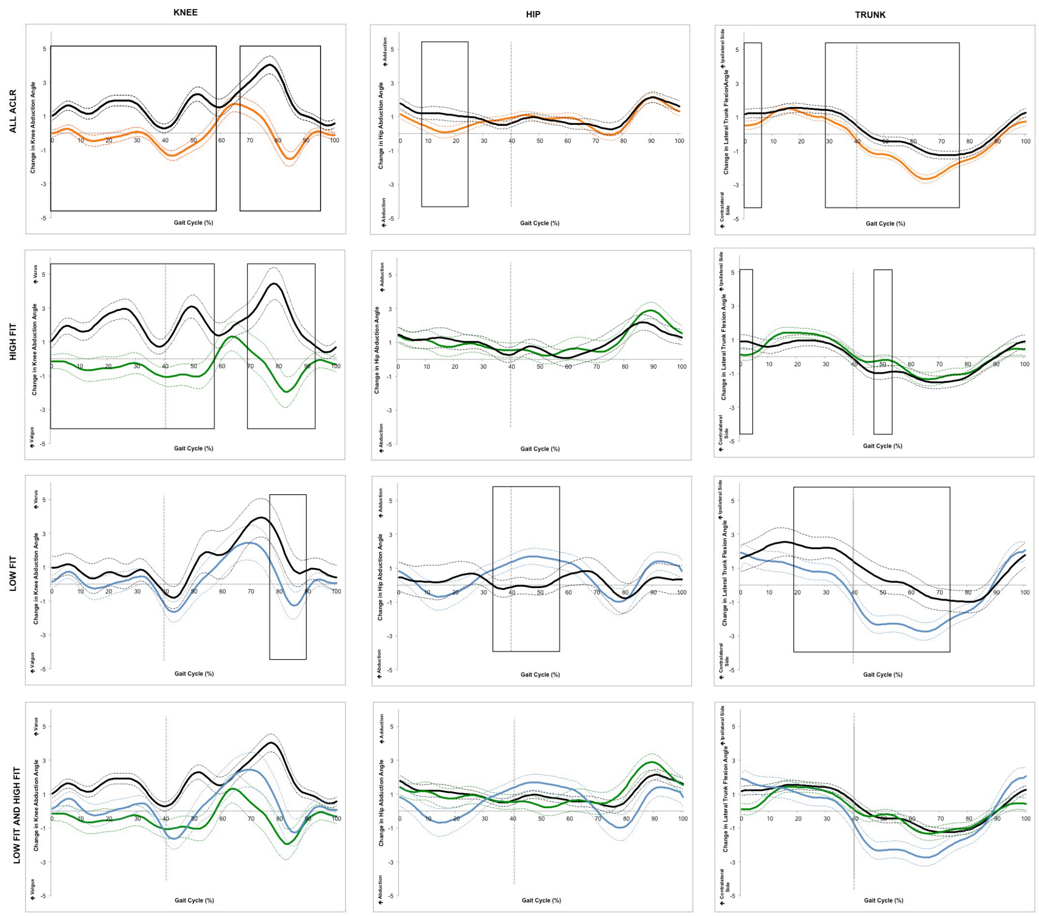

Figure 3. Mean change (degrees) in frontal knee, hip, and trunk kinematics after exercise over the gait cycle in all ACLR and all healthy, high fit ACLR and high fit healthy, and low fit ACLR and low fit healthy. Areas where 90% confidence intervals did not overlap for three or more consecutive points were considered statistically significant. The orange line represents all ACLR, the green line represents high fit ACLR, and the blue line represents low fit ACLR. The black line represents healthy. The vertical dashed line represents toe-off.

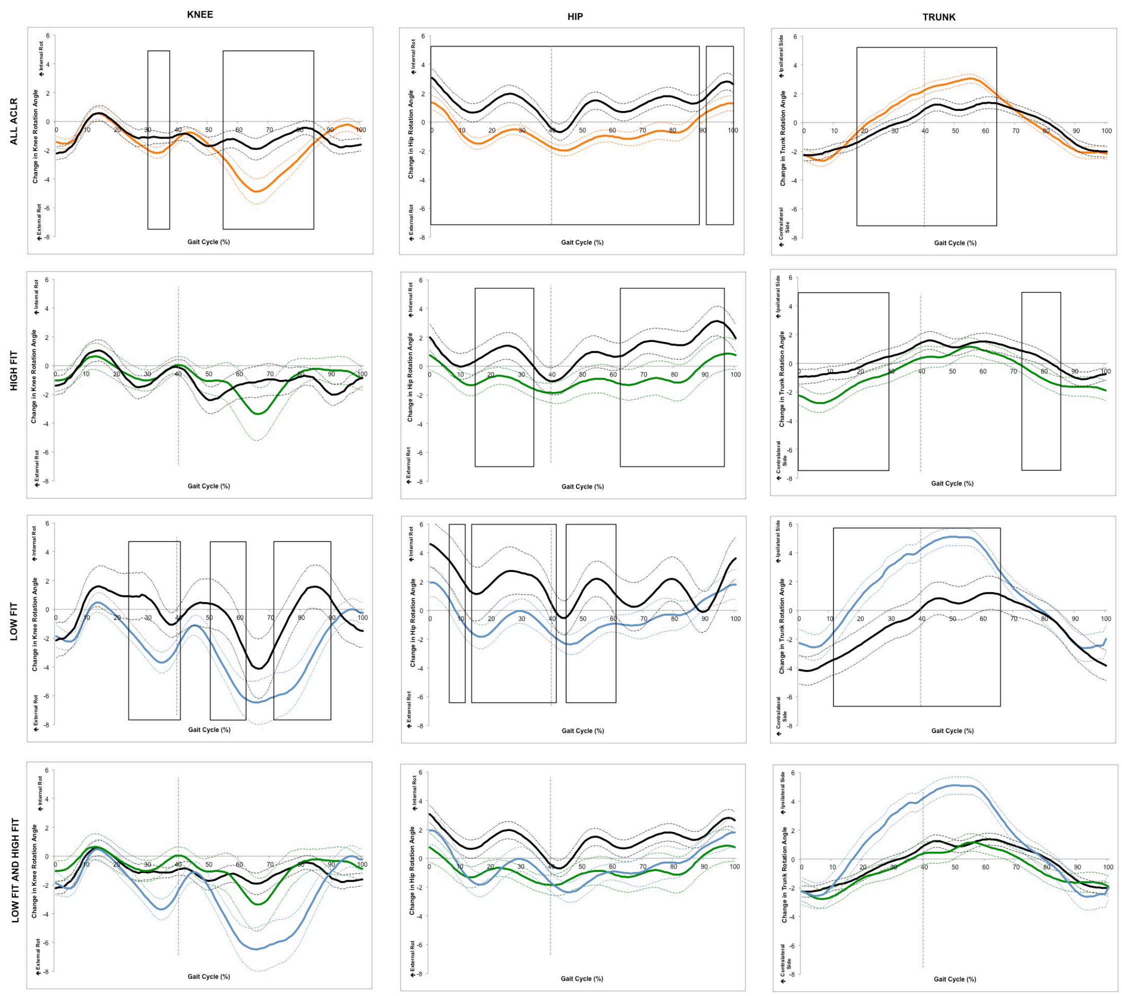

Figure 4. Mean change (degrees) in transverse knee, hip, and trunk kinematics after exercise over the gait cycle in all ACLR and all healthy, high fit ACLR and high fit healthy, and low fit ACLR and low fit healthy. Areas where 90% confidence intervals did not overlap for three or more consecutive points were considered statistically significant. The orange line represents all ACLR, the green line represents high fit ACLR, and the blue line represents low fit ACLR. The black line represents healthy. The vertical dashed line represents toe-off.

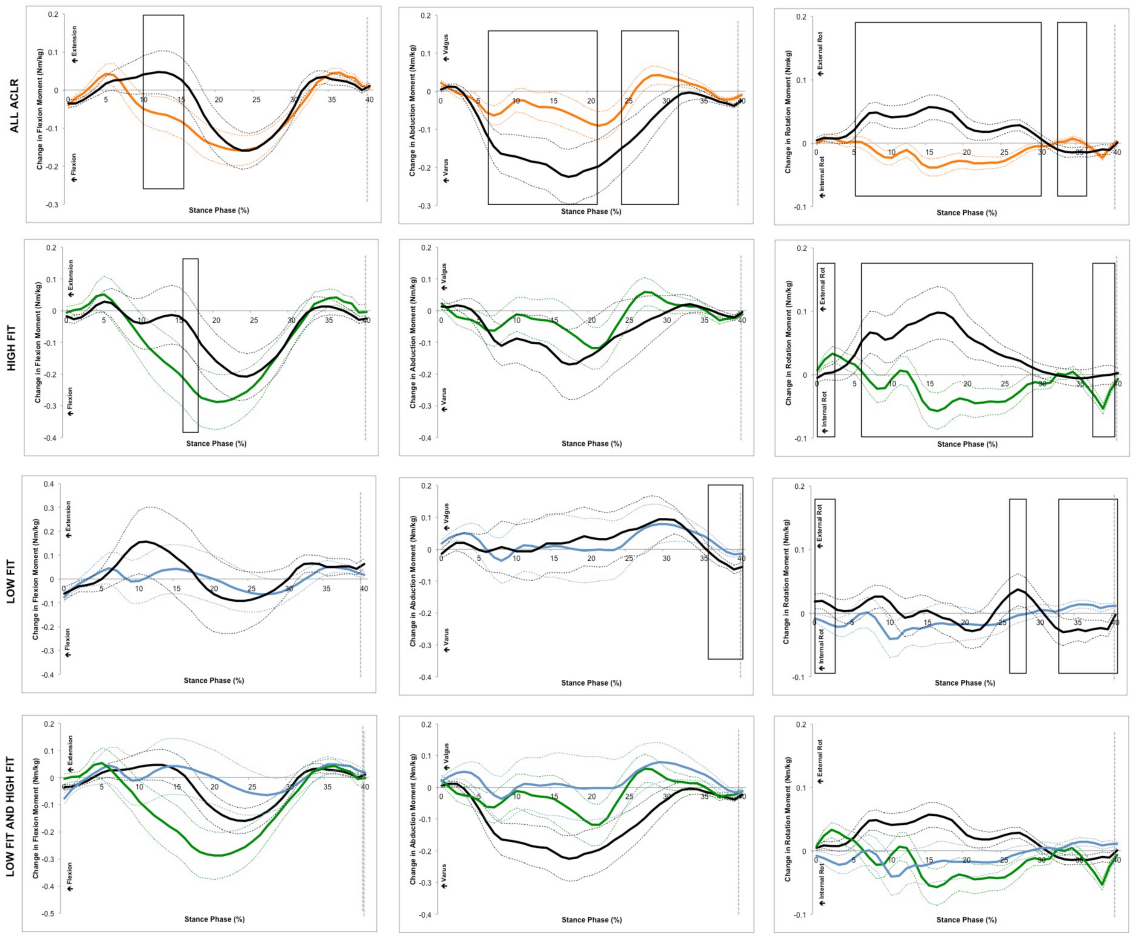

Figure 5. Mean change in sagittal, frontal, and transverse knee kinetics (Nm/kg) after exercise over the stance phase of gait (0-40%) in all ACLR, high fit ACLR, and low fit ACLR. Areas where 90% confidence intervals did not overlap for three or more consecutive points were considered statistically significant. The orange line represents all ACLR, the green line represents high fit ACLR, and the blue line represents low fit ACLR. The black line represents healthy. The vertical dashed line represents toe-off.

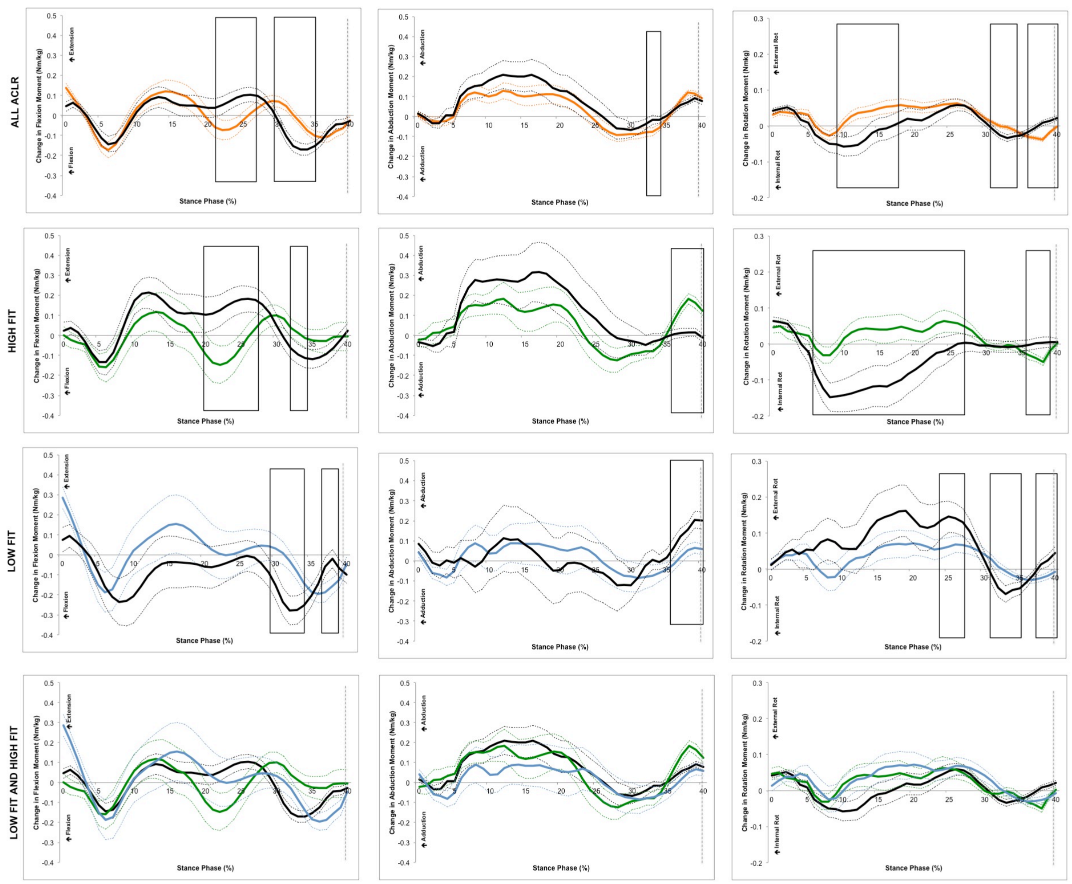

Figure 6. Mean change in sagittal, frontal, and transverse hip kinetics (Nm/kg) after exercise over the stance phase of gait (0-40%) in all ACLR, high fit ACLR, and low fit ACLR. Areas where 90% confidence intervals did not overlap for three or more consecutive points were considered statistically significant. The orange line represents all ACLR, the green line represents high fit ACLR, and the blue line represents low fit ACLR. The black line represents healthy. The vertical dashed line represents toe-off.

Section II: Manuscript III

Indicators of Performance Deterioration in ACL Reconstructed Individuals After Exercise

ABSTRACT

After anterior cruciate ligament reconstruction (ACLR), young athletes who return to a high level sport are at increased risk for subsequent knee injury. These injuries may be from exercise related biomechanical adaptations, but are difficult to measure in a clinic. The purpose of this study is to determine if objective measures of strength and functional performance predict asymmetry in running after ACLR and if strength and functional performance predict changes in running gait in individuals with ACLR after exercise.

Methods: Thirty-three individuals with history of ACLR (22F/11M, 19.9±2.2 years, 68.3±10.9 kg, 170.4±8.4 cm, 22.7±23.3 months post-surgery) completed one session for isokinetic strength and single leg hop for distance and a second session that included a modified square hop test and running gait analysis before and after exercise. Peak kinematic and kinetic gait variables during the first 20% of gait were calculated. Bivariate Pearson's correlations were calculated to identify relationships among changes in gait kinematics and kinetics and objective performance measures. All significant correlations ($P \leq 0.05$) were entered into a multiple regression analysis. A receiver operating characteristic (ROC) curve analysis was performed on variables that explained the most variance in gait for cutoff thresholds on objective strength and functional performance.

Results: Peak knee extensor torque symmetry explained considerable variance in hip

flexion (R^2 = 0.197), trunk flexion (R^2 = 0.264), and vertical ground reaction force (R^2 = 0.380) during running gait prior to exercise. The cutoff threshold for knee extensor torque symmetry for asymmetry in vertical ground reaction force was 85%. Symmetry on the modified square hop test explained some of the variance in hip flexion angle asymmetry (R^2 = 0.133) and hip rotation moment (R^2 = 0.122) before exercise as well as changes in hip flexion angle (R^2 = 0.222) and hip rotation moment (R^2 = 0.192) after exercise in the ACLR limb. **Conclusions:** Quadriceps strength symmetry is correlated with limb differences in running gait after ACLR however was not a predictor of changes after exercise. Changes in the modified square hop test did correlate with changes in hip motion, indicating that more functional and challenging tasks are more appropriate for return to sport decisions.

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common in athletic and recreationally active populations, with approximately 250,000 ACL injuries and 130,000 ACL reconstruction (ACLR) procedures occurring annually in the United States as of 2006.[38,61] After ACLR, the most commonly used objective criteria to return a patient to activity include quadriceps strength symmetry and functional performance in a rested state,[1,35] however ACL injuries happen occur most often during games[41] when neuromuscular fatigue may alter mechanics. Although deficits in quadriceps strength alter lower extremity kinematics and kinetics during gait and unilateral tasks,[21,56,82] it is unclear if objectively measured performance and strength deficits after ACLR predict changes after exercise.

Patients with ACLR demonstrate a quadriceps avoidance pattern during running, with decreased knee flexion and flexion moment and increased hip motion.[53,70] These sagittal plane deviations are often accompanied by increased lateral trunk flexion, knee adduction and external rotation.[69,87] The combination of decreased knee flexion and more proximal changes may be a method of decreasing eccentric work at the quadriceps during stance phase of running gait, especially when reduced quadriceps strength is present. Sagittal plane adaptations are evident in patients with decreased quadriceps strength,[53,56] however there is limited evidence to support a metric that predicts biomechanical adaptations during exercise both in a rested and fatigued state. Prediction of biomechanical adaptations may help inform decisions regarding the return to unrestricted physical activity in patients with ACLR who are at high risk for subsequent knee injury during sports participation.

Risk of injury is greatest at the end of games and season,[24,25]suggesting that adaptations to neuromuscular fatigue may play a role in injury risk. After ACLR, patients demonstrate changes in knee and hip motion[53] as well as altered quadriceps and hamstring activation during running gait after exercise.[77,78] Gait adaptations after ACLR may contribute to the increased risk of knee joint osteoarthritis (OA)[6] and subsequent ACL injury.[91] Almost 25% of all patients younger than 25 who return to a high level of sport experience a secondary ACL injury.[37,48,50,91] This increased risk for injury in young athletes with ACLR who return to their sport may be from partly due to persistent strength deficits and neuromuscular changes after initial reconstruction along with exposure to a high-risk environment, however these biomechanical adaptations are difficult and expensive to measure. Therefore, the purpose of this study was to (1) determine strength and functional performance predictors of running gait after ACLR and

(2) determine strength and functional performance predictors of changes in running gait in individuals with ACLR after fatiguing exercise.

METHODS

This was a descriptive laboratory study with a repeated measures design. The independent variables in this study were time (pre and post exercise) and objective measures of strength (peak torque, total work, and average power) and performance (single leg hop and modified square hop test). The dependent variables included sagittal, frontal, and transverse plane knee, hip, and trunk kinematics and sagittal, frontal, and transverse knee and hip internal moments normalized to mass (Nm/kg), and peak vertical ground reaction force normalized to mass (N/kg).

Subjects

Thirty-three individuals with history of primary, unilateral, uncomplicated ACLR (22 females/11 males, 19.9±2.2 years, 68.3±10.9 kg, 170.4±8.4 cm, 22.7±23.3 months post-surgery) volunteered to participate in this study. Reconstruction techniques included 18 bone-patellar-bone grafts, 14 hamstring grafts, and 1 allograft. All subjects provided written informed consent approved by our University's institutional review board for health sciences research.

Instrumentation

Torque, work, and power data were collected using the Biodex System 3 dynamometer chair (Biodex Medical Systems, Inc., Shirley, NY). A 12-camera motion capture system (Vicon Motion Systems, Ltd, UK; SEM = 0.75-2.3 degrees) and a split-belt instrumented treadmill (Bertec, Columbus, OH) were used to collect kinematic and kinetic data during running. Kinematic data were sampled at 250Hz and ground reaction forces were sampled at 1000Hz. Data were synchronized, exported, and filtered using a zero-lag fourth-order Butterworth filter at 14.5Hz using MotionMonitor software (Innovative Sports Training, Inc., Chicago, IL). An instrumented pressure mat (Just Jump Mat, Probotics, Inc., Huntsville, AL) was used for ground contact time and the FITLIGHT™ reaction light system (FITLIGHT Trainer, FITLIGHT Sports Corp., Aurora, Ontario) was for agility during the exercise session. A 3-meter tape measure was secured to the floor for single hop for distance. A heart rate monitor (Polar T31 Transmitter, Polar Electro Inc., Lake Success, NY) was fitted below the pectoral muscles during the exercise protocol. The 6-20 Borg Scale[10] was used to measure rate of perceived exertion (RPE) during the exercise protocol.

Strength and Performance Testing

All subjects came to the laboratory for two separate sessions separated by at least 48 hours. The first session included strength measures and single leg hop testing.[22] After walking on a treadmill for five minutes to warm up, subjects sat in the Biodex chair in approximately 85° of hip flexion with the axis of the dynamometer aligned to the lateral knee joint center. The distal end of the dynamometer arm was secured to the distal third of the subject's shank with a padded Velcro strap. Range of motion was set from 0° to 110° of knee flexion. Subjects crossed their hands on their shoulders with the back and head against the chair and a belt was secured over the subject's lap. After practice trials, subjects completed eight concentric repetitions of knee extension and knee flexion at 180°/s. Testing was completed on the uninvolved limb before completing testing on the involved limb. All strength measures were normalized to body mass (kg). Following strength testing, subjects completed the single-leg hop for distance. Subjects were instructed to hop as far as possible and stick the landing. Subjects completed three trials on each leg, starting with the uninvolved leg and alternating to the involved leg. Practice trials were encouraged to minimize a learning effect. Average distance of the three trials was calculated. Distance was measured from the start line to the subject's heel.

Gait Analysis

The second session included 30 minutes of exercise. Subjects wore a t-shirt, shorts, and their own athletic shoes appropriate for running. Subjects were set up with eight clusters of reflective markers attached to the thorax, sacrum, right and left mid-thigh, right and left mid-calf, and right and left forefoot.[14] The medial and lateral malleoli, medial and lateral knee joint lines, L5/S1, T12/L1, C7/T1, and left and right anterior superior iliac spine were digitized to identify joint centers. The subject walked and ran on the instrumented treadmill for five minutes before collecting twelve capture periods of two seconds each during running at 3.33m/s (7.5mph) before and after exercise.

Exercise Protocol

Subjects completed a modified square-hop test[12] by jumping in and out of a 40cm square within a 72cm square (instrumented pressure mat) as fast as possible (Figure1). If the entire foot did not clear the mat when jumping off the mat, the trial was repeated.

Subjects completed the modified square hop test in a clockwise pattern on the right foot and in a counterclockwise pattern on the left foot. All subjects were given practice trials before completing one trial on the uninvolved limb and then the involved limb. Total time to complete all eight jumps was recorded on each limb as well as average ground contact time (s) for the four jumps on the mat (Figure 1).

Immediately after running gait data capture, the subject started the exercise protocol which included five minutes of treadmill intervals accompanied with one minute of agility using the reactive light system. The treadmill intervals included 15 seconds of walking at 1.34 (3.0mph), 25 seconds of jogging at 2.68m/s (6.0mph), and 20 seconds of running at 3.33m/s (7.5mph). These specific interval velocities and durations were designed to simulate the proportions of walking, jogging, and running in a collegiate soccer match (unpublished data from our lab). The walk, jog, and run intervals were repeated five times for a total of five minutes of treadmill exercise. The one-minute of agility was completed immediately after the five minutes of treadmill exercise, with eight reactive lights set up in a semi-circle 3.5m from the subject (Figure 2). The lights illuminated in a random order and the subject was instructed to run as quickly as possible to touch the light and run backwards to the starting position when another light illuminated. Subjects were encouraged to touch as many lights as possible in one minute.

After the agility, subjects returned to the treadmill to repeat the intervals. Both the treadmill and agility (six minutes in total) were repeated five times to make up the 30 minutes of exercise. After completing the exercise protocol, subjects immediately returned to the treadmill and ran at 3.33m/s then retested the modified square hop test.

Data Processing

Knee, hip, and trunk sagittal, frontal, and transverse angles were reduced to 101 points to represent 0-100% of the gait cycle (heel strike to ispilateral heel strike). Heel strike was defined as the point when vertical ground reaction forces exceeded 20N.[93] Knee and hip sagittal, frontal, and transverse internal moments and vertical ground reaction forces were normalized to body mass and reduced to 41 points to represent 0-40% of the gait cycle from heel strike to toe off (when vertical ground reaction forces were less than 20N) to represent the stance phase of running gait.[53] Peak angles, internal moments, and forces were calculated for each subject and both limbs for the first 20% of gait. Differences between limbs for all gait metrics were calculated as the uninvolved limb subtracted from the involved limb. All performance and strength variables before exercise were expressed as limb symmetry by dividing the involved limb by the uninvolved limb. Changes after exercise were calculated as pre-exercise subtracted from post-exercise for all gait and performance changes in the involved limb.

Statistical Analyses

Paired t-tests were used to compare heart rate and RPE before and after exercise. Bivariate Pearson's correlations were calculated to identify relationships among changes in gait kinematics and kinetics and objective performance measures. Isokinetic strength outcomes included mass normalized peak torque, total work, and average power for knee extension and flexion. Functional measures included average hop distance on the single leg hop for distance, total time for the modified square hop test, and ground contact time for the modified square hop test. All significant correlations ($P \leq 0.05$) were retained for a multiple regression analysis. A stepwise linear regression model was used to identify proportion of variance explained in changes in gait kinematics and kinetics after exercise. A receiver operating characteristic (ROC) curve analysis was performed on variables that explained the most variance in hip flexion, knee abduction, and vertical ground reaction forces differences between the involved and uninvolved limbs before exercise using previously reported differences of 3.0 degrees,[85] 0.6 degrees,[85] 0.7 N/kg,[82] respectively. Only ROC curves that were statistically significant were evaluated for cut-off thresholds.

All analyses were run using SPSS and alpha level of 0.05 was set *a priori* (version 22.0, Chicago, IL).

RESULTS

Both heart rate (HR_{pre}= 87.39±17.04bpm, HR_{post} = 193.94±9.49bpm; P < 0.0001) and RPE (RPE_{pre} = 6.00±0.00, RPE_{post} = 18.64±1.43; P < 0.0001) significantly increased after exercise.

Inter-limb Differences During Pre-Exercise Running

Means and standard deviations for all gait differences, strength symmetry, and hopping symmetry measures are reported in Table 1 and 2. Side-to-side differences in knee abduction angle were significantly correlated with square hop time limb symmetry (*r* = -0.359, P = 0.040). When entered into the stepwise linear regression model, symmetry on square hop time explained 12.9% of the variance in side-to-side difference in knee abduction angle. The ROC curve using a side-to-side difference of 0.6° in knee abduction angle[85] was not significant (AUC = 0.529, P = 0.841, Sensitivity = 0.60, Specificity = 0.429). Side-to-side differences in hip flexion angle were significantly correlated with knee extensor peak torque symmetry (*r* = 0.444, P = 0.010), knee extensor total work symmetry (*r* = 0.360, P = 0.040), and knee extensor average power symmetry (*r* = 0.360, P = 0.039). All three variables were entered into the stepwise linear regression model and the only variable retained in the model was knee extensor peak torque symmetry (P = 0.010), which explained 19.7% of the variance in side-to-side difference in hip flexion angle. The ROC curve using a side-to-side difference of 3.0° in hip flexion between limbs[85] was not significant (AUC = 0.609, P = 0.327, Sensitivity = 0.478, Specificity = 0.30).

There were four variables significantly correlated with side-to-side differences in trunk flexion between limbs including peak knee extensor torque symmetry (*r* = -0.351, P = 0.045), knee extensor total work symmetry (*r* = -0.416, P = 0.016), knee extensor average power symmetry (*r* = -0.514, P = 0.002), and modified square hop time symmetry (*r* = 0.337, P = 0.055). When entered into the regression model, the only variable retained in the model was knee extensor peak symmetry (P = 0.002), which explained 26.4% of the variance in side-to-side difference in trunk flexion. Symmetry in ground contact time during the modified square hop test was the only one variable was significantly correlated with side-to-side difference in trunk rotation (*r* = -0.375, P = 0.032), which explained 14.1% of the variance. There were four variables significantly correlated with side-to-side differences in vertical ground reaction forces including peak knee extensor torque symmetry (r = 0.616, P < 0.0001), knee extensor total work symmetry (r = 0.527, P = 0.002), knee extensor average power symmetry (r = 0.562, P = 0.001), and single leg hop symmetry (r = 0.414, P = 0.017). All four variables were entered into the stepwise linear regression model and only peak knee extensor torque symmetry was retained in the model and explained 38.0% of the variance in vertical ground reaction forces between limbs (P < 0.0001). A cut-off threshold was calculated for peak knee extensor torque symmetry in vertical ground reaction forces using a side-to-side difference of 0.7.[82] The cutoff threshold for knee extensor torque symmetry was 85% (AUC = 0.870, P < 0.001, Sensitivity = 0.89, Specificity = 0.27).

Pre-Post Exercise Running Gait in the Involved Limb

Pre-Exercise Measures

Mean changes in gait and functional tests are reported in Table 3. There was a significant correlation between modified square hop time symmetry before exercise and change in hip flexion angle in the involved limb (r = -0.364, P = 0.019), which explained 13.3% of the variance (P = 0.037). Modified square hop time symmetry before exercise was also correlated with change in hip internal rotation moment (r = -0.349, P = 0.023) before and after exercise and explained 12.2% of the variance (P = 0.047).

Pre-Post Exercise Measures

There was a significant correlation between change in hip flexion angle and change in modified square hop test ground contact time in the involved limb (r = 0.471, P = 0.006), which explained 22.2% of the variance. Change in modified square hop ground contact time was also significantly correlated with change in internal hip rotation moment in the involved limb (r = -0.438, P = 0.011) and explained 19.2% of the variance in hip rotation moment. There were no other significant correlations between changes in gait and strength and performance measures.

DISCUSSION

The aim of this study was to predict limb asymmetry during running gait after ACLR using strength and functional performance. The main variables that predict limb asymmetry during running gait are quadriceps strength symmetry and the modified square hop test. Quadriceps strength asymmetry is one of the most commonly reported measures in return to activity testing and low strength symmetry is present in both isometric and isokinetic testing around time of return to sport[76,94] despite evidence that strength deficits are associated with altered movement patterns during functional tasks.[47,65,76,82] Low symmetry (<80%) has also been associated with decreased sagittal plane motion at the knee during walking and jogging gait.[53,56] Quadriceps strength symmetry was also associated with changes in the sagittal plane in the subjects in this study, however in more proximal joints. This may be due to the increased gait speed in our study, causing patients to alter hip and trunk motion rather than knee flexion during high-speed running.

These asymmetries during running are concerning considering running is one of the first functional tasks patients are cleared to perform after ACLR, with many patients returning to running approximately 4 months after surgery.[28,83] There is evidence supporting that force loading asymmetries are present when cleared to return to running,[69,83] however running is still incorporated into rehabilitation based on a set time-based progression of activities.[2] The regression model in this study identified peak knee extensor torque symmetry as a strong predictor of peak vertical ground reaction force symmetry during loading and early stance phase of running gait. The model explained a large proportion of the variance and the cut-off threshold of 85% symmetry was associated with an AUC value of 0.870 suggesting that the predictive ability of this cut-off point is very good. Quadriceps strength symmetry around 85-90% is often considered appropriate to release someone to full activity, however there may be some utility in achieving 85% symmetry before incorporating running into rehabilitation. Running makes up over a half a soccer game[90] and returning someone back to a this environment without establishing symmetrical loading patterns may predispose these athletes to OA. Loading asymmetry during gait can lead to changes in cartilage loading patterns, contributing to the high incidence of joint OA after ACLR.[6] Delaying return to running until a patient is more symmetrical in quadriceps strength may postpone joint OA.

As opposed to strength symmetry, functional performance was a predictor of changes in gait after exercise. This supports rehab progression from strengthening to functional tests before returning to activity, however the most commonly used functional test before release to activity is the single leg hop for distance.[1] The single hop for distance was only correlated with peak vertical ground reaction forces, however was not retained in the model and was not correlated with any changes in gait after exercise. Therefore, symmetry on the single hop for distance may not be the most appropriate test to clear someone to participate in a sport environment. The modified square hop test requires balance and speed to perform the multi-planar movement rather than explosive strength and power of the single leg hop.[46,66,88]

Although performance on the modified square hop test did correlate with some changes in gait, increased average ground contact time and total time to complete the task was only associated with changes at the hip. Increased ground contact time after exercise was associated with increased hip flexion and decreased transverse hip moment. After exercise, patients with ACLR often demonstrate reduced hip extensor strength, which may be the result from increased hip involvement when rested causing the hip musculature to fatigue quickly.[17,53] Decreased hip strength after exercise coupled with decreased knee extensor strength may increase time between gross movements on the hop test, while decreased transverse plane joint attenuation may be associated with decreased trunk motion in an effort to increase stiffness and stability.[14,72] Changes in ground contact time on the square hop test may be an appropriate measure to evaluate athletes who rely on hip strength during running gait when fatigued. These changes in hip mechanics were also correlated with symmetry on the modified square hop test for total time, and therefore this may be a useful test that can be completed in a rested state to predict hip motion after exercise. However, the modified square hop test still only explained a small amount of the variance in changes in hip motion, suggesting that other factors should be considered when returning an athlete back to sport.

There were a few limitations in the current study. This study did not consider time from surgery, which may be a contributing factor to changes in running gait, however changes in gait persist years after ACLR.[85,87] The ACLR group also included multiple surgical techniques and included both men and women. The patient population in this study represents a sample of patients in a clinic, with more patellar tendon grafts and women. Lastly, reflective markers were placed on the subject before running and were not removed for exercise. We made this decision to minimize time between completion of the exercise and post-exercise running collection. The markers were secured with tape to reduce chance of movement.

CONCLUSIONS

Quadriceps strength symmetry is correlated with limb differences in running gait after ACLR. Knee extensor peak torque symmetry is the most predictive variable for symmetrical vertical ground reaction forces during running and 85% symmetry on knee extensor strength may be a useful threshold for incorporation of running into rehabilitation. Strength symmetry was not a predictor of changes after exercise, however changes in functional tests did correlate with changes in hip motion, indicating that more functional and challenging tasks may be more appropriate for predicting changes in gait after exercise.

Table 1. Mean and standard deviations for all symmetry measures. Limb symmetry was calculated as the involved limb (ACLR) divided by the uninvolved limb (contralateral). A symmetry value of 1.0 was interpreted as perfect symmetry and a value less than 1.0 indicates the uninvolved limb outperformed the involved limb.

Knee Extension Symmetry	
Variable	Mean Symmetry
Peak Torque at 180°/s	0.89 (0.13)
Total Work at 180°/s	0.90 (0.13)
Power at 180°/s	0.91 (0.12)
Knee Flexion Symmetry	
Variable	Mean (Standard Deviation)
Peak Torque at 180°/s	1.00 (0.17)
Total Work at 180°/s	1.05 (0.26)
Power at 180°/s	1.06 (0.26)
Functional Symmetry	
Variable	Mean (Standard Deviation)
Single Hop	0.95 (0.07)
Square Hop Time	1.02 (0.10)
Square Hop Ground Contact Time	1.04 (0.20)

Table 2. Mean difference and standard deviations for limb differences in gait metrics. Differences were calculated as the uninvolved limb (contralateral) subtracted from the involved limb (ACLR). A negative value indicates the ACLR limb had increased extension, abduction, or external rotation for kinematic variables (degrees). For kinetic variables, a negative value indicates the ACLR limb had increased internal extension moment, abduction moment, and external rotation moment (Nm/kg).

Kinematics	
Variable	Mean Difference
Knee Flexion (°)	-4.21 (5.72)
Knee Abduction (°)	-1.27 (5.87)
Knee Rotation (°)	-4.51 (8.95)
Hip Flexion (°)	-1.59 (2.68)
Hip Abduction (°)	0.54 (4.68)
Hip Rotation (°)	-2.19 (9.30)
Trunk Flexion (°)	0.26 (1.52)
Trunk Lateral Flexion (°)	0.73 (4.82)
Trunk Rotation (°)	-2.04 (7.65)
Kinetics	
Variable	Mean (Standard Deviation)
Knee Flexion Moment (Nm/kg)	-0.28 (0.79)
Knee Abduction Moment (Nm/kg)	0.24 (0.90)
Knee Rotation Moment (Nm/kg)	-0.08 (0.20)
Hip Flexion Moment (Nm/kg)	0.06 (0.83)
Hip Abduction Moment (Nm/kg)	-0.25 (0.78)
Hip Rotation Moment (Nm/kg)	0.15 (0.36)
Vertical GRF (N/kg)	-0.51 (0.97)

Table 3. Differences (Post – Pre) in the involved (ACLR) limb before and after exercise for all gait metrics and functional tests. For gait metrics, a negative value indicates the ACLR limb had increased extension, abduction, or external rotation for kinematic variables (degrees) after exercise. For kinetic variables, a negative value indicates the ACLR limb had increased internal extension moment, abduction moment, and external rotation moment after exercise (Nm/kg).

Kinematics	
Variable	Mean Difference
Knee Flexion (°)	-0.52 (2.50)
Knee Abduction (°)	-0.53 (4.24)
Knee Rotation (°)	3.38 (7.45)
Hip Flexion (°)	-1.45 (3.70)
Hip Abduction (°)	0.62 (2.68)
Hip Rotation (°)	1.37 (8.60)
Trunk Flexion (°)	-0.13 (2.87)
Trunk Lateral Flexion (°)	1.40 (5.62)
Trunk Rotation (°)	-2.25 (3.79)
Kinetics	
Variable	Mean (Standard Deviation)
Knee Flexion Moment (Nm/kg)	-0.07 (0.35)
Knee Abduction Moment (Nm/kg)	-0.06 (0.16)
Knee Rotation Moment (Nm/kg)	-0.05 (0.13)
Hip Flexion Moment (Nm/kg)	-0.02 (0.31)
Hip Abduction Moment (Nm/kg)	0.15 (0.26)
Hip Rotation Moment (Nm/kg)	0.02 (0.14)
Vertical GRF (N/kg)	0.98 (0.91)
Functional Tests	
Variable	Mean (Standard Deviation)
Square Hop Time (s)	-0.11 (0.35)
Square Hop Ground Contact Time (s)	-0.02 (0.06)

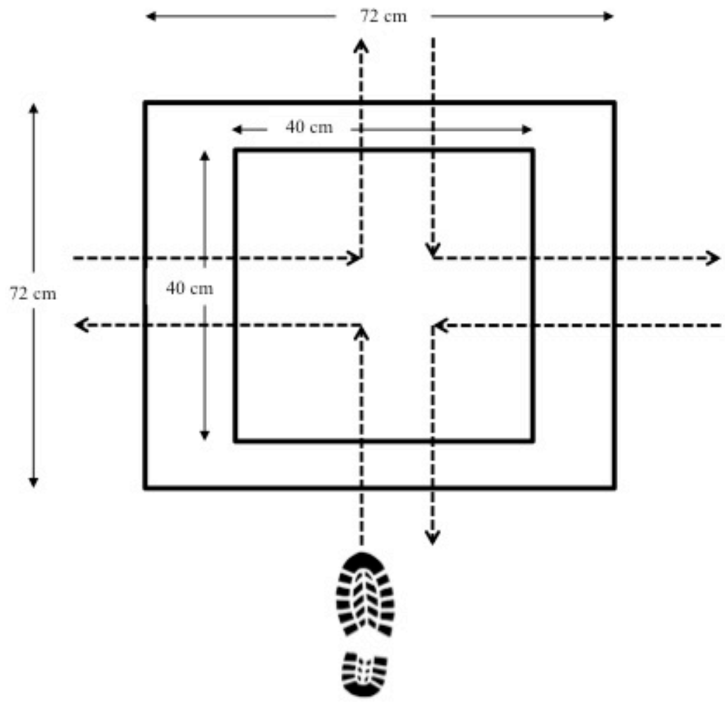

Figure 1. The modified square hop test was performed by hopping in and out of the 72 x 72cm jump mat as fast as possible. Subjects jumped within the 40 x 40cm square taped on the jump mat when jumping on the mat and had to clear the entire jump mat when jumping off the mat. Subjects completed one clockwise rotation (8 total jumps) on the right leg and one counterclockwise rotation (8 total jumps) on the left leg.

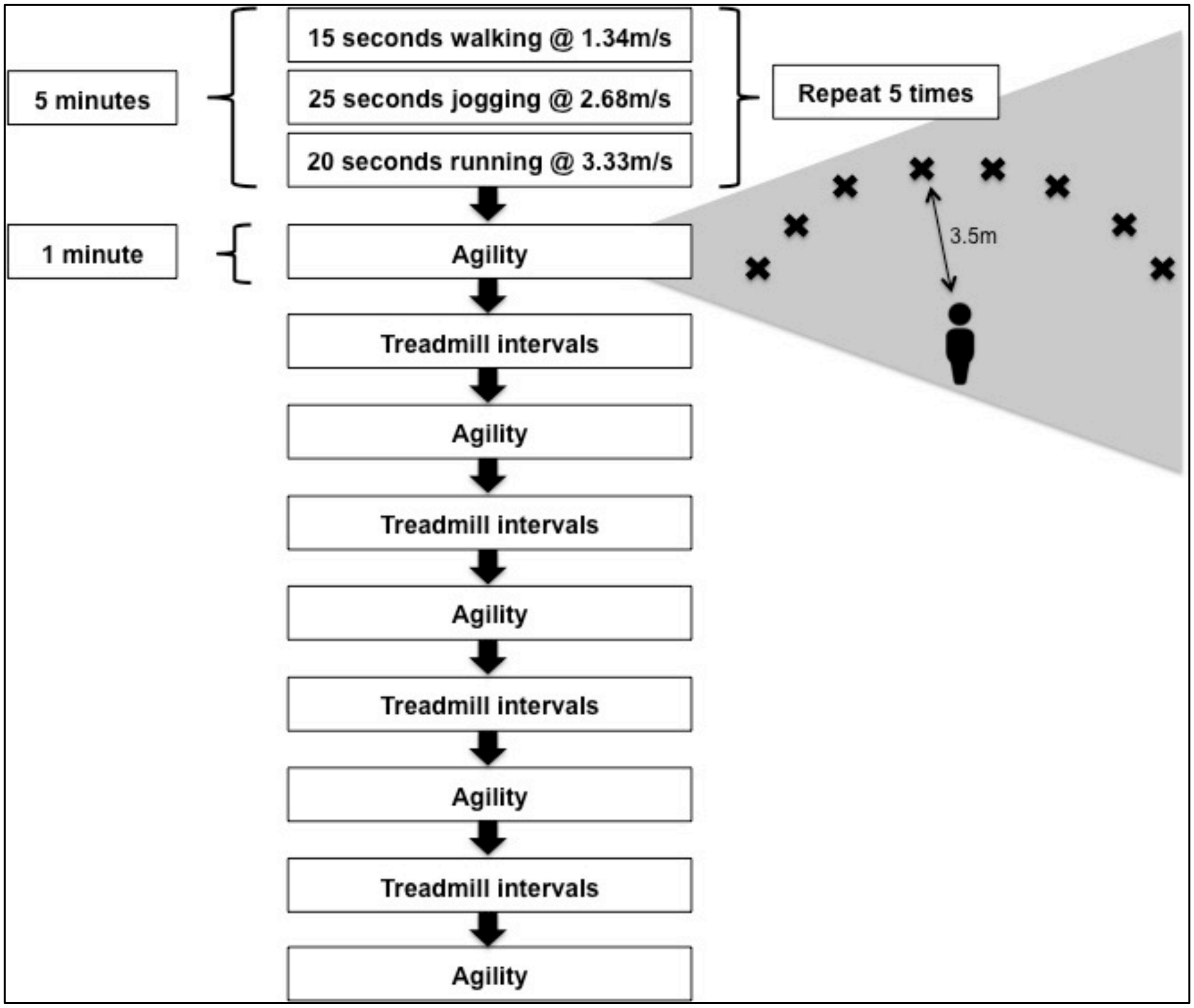

Figure 2. The exercise protocol used in this study included five sets of treadmill intervals combined with one minute of agility. The agility portion used eight reactive lights set up 3.5m from the subject. The subject ran to touch an illuminated light as quickly as possible, backpedaled back to the starting position and ran to touch the following light.

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APPENDIX A

The Problem

<u>Problem Statement:</u>

Anterior cruciate ligament (ACL) injuries are commonplace, with approximately 250,000 ACL injuries and 130,000 ACL reconstruction (ACLR) procedures occurring annually in the United States as of 2006.[84,130] More than 2,000 of these ACL injuries occur in collegiate athletics, most commonly seen in lacrosse, basketball, and soccer.[23,86] Knee injuries are the second most common lower extremity joint injury in collegiate athletics,[86] however knee injuries are the most common injury resulting in more than 10 days of activity time loss in soccer.[48] Although most patients attempt to return to sport after ACLR, less than 40% return to sport at 12 months post-ACLR,[193] and less than 30% are able to return to competitive sports 2-7 years post-ACLR.[10] Even in professional athletics, not all athletes are able to return to sport after ACLR.[51] ACL injuries may therefore be career ending injuries for high school and college athletes who cannot return to pre-injury level after ACLR.

Although patients often undergo ACLR to return to pre-injury level of sport, many patients experience persistent reductions in knee function after ACLR,[11,143] such as deficits in quadriceps activation and strength[73,106,107,144] as well as a shift towards fatigue-resistant quadriceps.[103,132] After ACLR, individuals also experience alterations in walking gait compared to healthy individuals years after surgery, including reductions in peak knee flexion angle, knee flexion moment, and knee extension moment during stance phase.[60,199,202] Alterations in walking gait after ACLR are concerning due to the increased risk of subsequent ACL injury[151] as well as hypothesized changes to cartilage loading patterns which may contribute to the increased risk of knee joint osteoarthritis compared to healthy individuals.[17]

Current return to sport evaluations include patient-reported outcomes, strength testing, and functional assessment.[12,147,174] Patient-reported outcomes are the most common tools for assessing return to play readiness, often using the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC),[7,89] Knee Injury and Osteoarthritis Outcome Score (KOOS),[169] and Tegner activity scale.[32,71,188] Poor subjective outcomes have been associated with poor quadriceps strength after ACLR[208] and single leg hop performance,[164] which are the most commonly used assessments for return to sport decision-making.[2,71] These tasks are completed in a rested state which may not be the most appropriate way to evaluate return to sport readiness, particularly for young athletes returning to high level athletics. Young athletes (<19 years old) tend to have better outcomes at 6 months post-ACLR and are returned to sport,[102] however these athletes are at increased risk for secondary ACL injury [83,92,171] and have higher risk of developing knee joint osteoarthritis.[121,195] Therefore, it is imperative that return to sport assessments for this population include functional assessments during exercise when risk of second injury is greatest and neuromuscular control is compromised.[19,28,173]

Individuals with ACLR exhibit muscular and biomechanical adaptations after exercise. These changes include decreased hip flexion angle, external hip flexion moment, and increased external knee flexion moment during jogging.[104] Furthermore, individuals with ACLR demonstrate altered quadriceps and hamstring activation after high-intensity exercise.[152,153] No changes in muscle activation have been noted after moderate-intensity exercise.[152] This supports evaluating individuals with ACLR when fatigued for patients attempting to return to high-intensity exercise, however there is no current model of laboratory-based fatiguing exercise that simulates movements experienced by an athlete during a game or match. Exercise protocols widely vary between research studies, ranging from localized muscle fatigue induced through isokinetic exercise to sport-specific exercise predominantly comprised of walking.[122,138]

There is a need for an evidence-based exercise protocol that combines the endurance, speed, agility, and decision-making during high-intensity exercise experienced by a high-level athlete.

The exercise protocol used in this study was designed using data extracted from global positioning system units worn by the University of Virginia men's soccer team. Proportions for walking, jogging, running, high-intensity running, and sprinting were calculated for 19 matches during the 2015-2016 season (Figure B3). These data have helped us design a laboratory-based exercise protocol that best simulates the movement profiles that high-level athletes are exposed to during matches. Soccer was selected because of the high rate of ACL injuries in collegiate soccer.[23,86] Preliminary data (n = 14) support that the exercise protocol used in this study elicits a post-exercise heart rate similar to those reported after a soccer match (183±14 bpm),[126] and is the most appropriate to understand how an individual with ACLR responds to sport-specific exercise in a controlled environment. Information about muscular and biomechanical adaptations and behaviors during higher velocity maneuvers at a fatigued state is important to guide return to sport decision making after ACLR.

Neuromuscular adaptations after ACLR are difficult to evaluate in a clinic without expensive equipment. There is a need for a clinic-friendly measure that is easy to perform, affordable, and can be done in a variety of settings, to evaluate performance deterioration in individuals with ACLR. The most common methods of evaluating readiness to return to sport after ACLR are quadriceps strength and functional performance on hopping tests,[2,71] however is it unclear if symmetry on these tests predict changes in running gait after exercise when injury risk is highest.

Therefore, the specific aims for this study are:

- To compare lower extremity gait mechanics after generic exercise and sport-specific exercise based on fitness level
- To compare changes in lower extremity gait mechanics between healthy individuals and individuals with ACLR after sport-specific exercise
- To determine the relationship between strength and performance and changes in gait mechanics before and after sport-specific exercise in healthy individuals and individuals with ACLR.

Research Questions:

1. **Do exercise-related adaptations in lower extremity movement patterns differ between a modified graded treadmill protocol and a data-driven exercise protocol? Does fitness level influence these differences?**

Hypothesis 1: Lower fit individuals will demonstrate increased changes in kinematics and kinetics during stance phase of running gait after data-driven exercise compared to higher fit individuals.

Hypothesis 2: Lower fit individuals will demonstrate increased changes in kinematics and kinetics during stance phase of running gait after a graded treadmill exercise protocol compared to higher fit individuals.

2. **Do data-driven exercise-related adaptations in lower extremity movement patterns differ between healthy individuals and individuals with ACLR?**

Hypothesis 1: Individuals with ACLR will demonstrate decreased knee extension moment and increased hip flexion moment during loading phase of running gait after exercise compared to healthy individuals.

Hypothesis 2: Individuals with ACLR will demonstrate increased net power absorption at the hip and trunk during loading phase of running gait compared to healthy participants after exercise.

3. **Can rested values and changes in clinical performance predict changes in peak kinetics after exercise?**

Hypothesis 1: Asymmetry in quadriceps strength will predict changes in sagittal plane gait kinematics and kinetics after exercise.

Hypothesis 2: Asymmetry in hopping performance will predict changes in frontal and transverse plane gait kinematics and kinetics after exercise.

<u>Assumptions:</u>

- Healthy participants were honest about lower extremity injury history
- Healthy participants in this study were representative of normal kinematic motion
- Passive reflective markers were representative of boney structures
- Kinematic and kinetic motion on treadmill is similar to that of normal flat surface walking and jogging
- Treadmill running is representative of flat ground running
- Participants provided maximal effort on knee extension tasks and exercise

Delimitations:

- Participants were recreationally active between 15-40 years old
- Participants with ACLR had primary, unilateral and uncomplicated reconstruction
- Healthy participants had no history of significant knee injury
- Participants with ACLR were cleared to return back to activity by orthopaedic surgeon
- Participants with ACLR were within 6 years of reconstructive surgery
- Participants with ACLR show no signs of early-onset posttraumatic osteoarthritis
- The exercise protocol modeled activity proportions of competitive college soccer

Limitations:

- There was no standardized surgical technique for ACL reconstruction
- Participants were not competitive college soccer players
- Participants were included in the study if they were within 6 years of reconstruction
- Treadmill speed was standardized for all participants for exercise protocols and collection speeds

Operational Definitions:

- **Rating of Perceived Exertion (RPE):** Subjective measure of exercise intensity from 6 (rest) to 20 (maximal effort) [27]
- **Fitness Level:** Defined by maximal oxygen consumption on a treadmill test. Subjects were divided into higher and lower fitness groups based on the median of the entire group
- **Gait Cycle:** Defined as heel strike to ipsilateral heel strike and reduced to 101 frames to represent 0-100% of gait[104]
- **Generic exercise:** Exercise using the modified Balke protocol[104]
- **Heel Strike:** When vertical ground reaction forces > 20N[206]
- **Primary, Unilateral, Uncomplicated ACL Reconstruction:** No history of previous or contralateral ACL injury or reconstruction and no other knee ligament tears. Concomitant injury to the meniscus will be included because of the frequent meniscal injury associated with ACL rupture
- **Return to Activity:** Cleared to resume unrestricted physical activity after anterior cruciate ligament reconstruction by physical therapist, athletic trainer, and/or orthopaedic surgeon

- **Significant Difference During Gait:** Areas during the gait cycle when confidence intervals do not overlap for three of more consecutive points.[104]
- **Sports-Specific Exercise:** Laboratory-based exercise that simulates activities experienced during live play using global positioning data from a men's Division I collegiate soccer team over an entire season.
- **Stance Phase:** 0-60% of walking gait cycle; 0-40% of running gait cycle
- **Swing Phase:** 60-100% of walking gait cycle; 40-100% of running gait cycle

Innovation:

Returning an athlete safely back to sport after injury is a priority for sports medicine professionals. We often evaluate strength, alignment, and walking mechanics at a rested state before clearing an athlete to return to sport, however the way the involved limb behaves when fatigued during higher velocity movements is important to appreciate return to sport readiness. Athletes should be evaluated in a fatigued state given that healthy athletes demonstrate adaptive landing strategies and gait patterns when fatigued.[22,133,145,148] More importantly, neuromuscular fatigue may increase risk of recurrent injury.[49,50,78] Sports medicine professionals must include assessments during higher velocity maneuvers at a fatigued state to guide return to sport decision making after ACLR.

Exercise used to elicit fatigue should simulate the movements athletes will experience during play. Current exercise protocols widely vary between studies, often ranging from localized muscle fatigue induced through isokinetic and isometric exercises[122] to sport-specific exercises.[104,177,181] Although exercise protocols mimicking soccer exist, the relative time spent walking comprises about half of the total exercise protocol,[138] which is not supported by time motion analyses in soccer and are influenced by level of play. College players spend less time walking compared to professional players.[30,196] Furthermore, all current time motion analyses in soccer only represent a single soccer match which may not best represent the demands an athlete experiences over the course of season (Table B-1).

The exercise protocol used in this study was designed using data extracted from global positioning system units worn by the University of Virginia men's soccer team. Proportions for walking, jogging, running, high-intensity running, and sprinting were calculated for 19 matches during the 2015-2016 season (Figure B-6). These data have helped us design a laboratory-based exercise protocol that best simulates the movement profiles that high-level athletes are exposed to during matches. The protocol also includes decision-making to mimic unanticipated events that occur during an actual soccer game. Given the nature of the sport, it can be assumed that most of the 5,000 turning events during a soccer game[25] are in response to movement on the field and require some level of decision-making.[118,166] Furthermore, athletes display altered kinematics and muscle recruitment strategy during unanticipated maneuvers in a fatigued state, indicating that injury risk may increase with neuromuscular and cognitive fatigue.[19,28,173]

This study served as the first step to identifying adaptive movement patterns in individuals with ACLR after a bout of sport-specific fatiguing exercise. This information will help guide return to play decision-making after ACLR.

APPENDIX B

Review of Literature

Incidence of Anterior Cruciate Ligament Injuries

Anterior cruciate ligament (ACL) tears are devastating injuries that have become commonplace in today's society with an estimated 250,000 ACL injuries annually in the United States[26] with an annual incidence of about 69 isolated ACL tears per 100,000 person-years.[171] Despite the contact nature of many sports, more than 70% of ACL injuries occur from noncontact mechanisms such as cutting, pivoting, sudden changes in direction, and jump landing.[67,96] These movements are common in soccer and basketball, which have the greatest number of reported ACL injuries in both high school and college,[4,23,86,194] most often in those 15-18 years old.[194]

Along with sport, sex also plays a role in ACL injury risk. Females are at increased risk for ACL injury compared to their male counterparts.[23,67,85,86,184,194] ACL injury rate ratios (IRR) are higher for female than male athletes in both high school (IRR = 2.30) and college (IRR = 2.49).[184] These sex differences are not similar for meniscal and medial collateral ligament injuries at either the high school or collegiate level, indicating that sex differences in ACL injuries are unique.[184] ACL injuries have declined significantly in males over the past two decades, however have remained relatively constant in females.[171]

Meniscal injuries often occur in conjunction with ACL injury.[34,94] Tears in the medial meniscus are more common than the lateral meniscus.[186] Injuries in the medial meniscus are also more common after initial ACL injury.[160,186] ACL injury with concomitant meniscal damage has been associated with worse subjective outcomes as well as increased prevalence of osteoarthritis.[17,40,102] ACL injuries with concurrent meniscal damage requiring surgical intervention significantly shortens professional sports careers comparing to an ACL injury alone.[33]

After ACL injury, most patients opt to undergo ACL reconstruction (ACLR) surgery with approximately 130,000 annual reconstructions in the United States as of 2006.[130] The two most common surgical techniques for reconstruction include bone-patellar tendon-bone (BPTB) and hamstring autograft (HG).[157] About 45% of reconstructions use the BPTB autograft compared to approximately 36% with HG, with the remaining 19% of reconstructions using an allograft.[83,92] Both autograft reconstructions (BPTB and HG) are currently more common than allograft reconstructions.[83,92] Autograft choice does not alter clinical outcomes after ACLR,[81] with exception to increased anterior knee and kneeling pain with BPTB.[127]

Risk Factors Associated with ACL Injury

ACL injuries are more common in games than practices.[4,5,63,69,86] This increased risk of injury during games may be due to adaptive movement patterns responding to unanticipated events, including increased lateral trunk flexion, knee abduction moment, and decreased hip abduction.[19,87] Knee valgus and trunk motion have been associated with increased risk of ACL injury.[58,67,85,100,146] Although prevention programs are appropriate for educating patients about risky movement patterns,[67] athletes often do not consider knee alignment and movement patterns at the end of games when athletes are fatigued.

ACL injury risk is greatest at the end of games and season.[49,50,78] Athletes display altered kinematics and muscle recruitment strategy during unanticipated maneuvers in a fatigued state, indicating that injury risk may increase with neuromuscular and cognitive fatigue.[19,28,173] Although stiff landings have been hypothesized as a main contributor to ACL injury risk,[46] vertical stiffness does not increase during landings after exercise.[145] Despite lack of changes in stiffness in fatigued conditions, both men and women demonstrate increased quadriceps-hamstrings co-activation as well as increased gastrocnemius activation when fatigued.[145] Increased hamstring and gastrocnemius cocontraction during knee flexion decreases strain at the ACL[57,88,109,125,135] and therefore these patterns may be in an effort to stabilize the knee joint after exercise.

Risk factors associated with ACL injuries are also different between males and females. Female risk for noncontact ACL injury increases with a parent with history of ACL injury, anterior posterior knee displacement, trunk flexion strength, and body mass index while male risk increases with anterior-posterior knee displacement, posterior knee stiffness, navicular drop, and standing quadriceps angle.[194] Females who demonstrate increased ground reaction force and knee abduction moment during landings are also at increased risk for ACL injury.[58,85] Females tend to exhibit these risky movements during athletic tasks such as side-cutting and cross-cutting which are associated with ACL injury.[129]

Risk Factors Associated with Secondary ACL Injury

Regardless of reconstruction technique, one of the most alarming things about ACL injury is the increased risk of secondary injury. The strongest predictor of injury is history of previous injury.[59,69,182] After ACLR, risk of ipsilateral graft failure and contralateral ACL injury is greatest during the first 24 months after surgery[150,151] and in patients under 25 years old.[93] Up to 15% of patients have a second ACL injury, either to the ipsilateral or contralateral knee.[203] Secondary ACL injury rate increases for younger patients and for athletes who return to their sport. Almost 25% of all patients younger than 25 who return to sport experience a secondary ACL injury.[83,203] Secondary ACL injury is further increased for patients younger than 18 compared to patients who are 18-25 years old,[83] suggesting that young athletes (14-18) who are at increased risk for primary ACL injury[171] are more likely to experience a second ACL injury after returning to high level of sport.[92,95] This increased risk for secondary injury in young athletes who return to their sport may be from persistent strength deficits and neuromuscular changes after initial reconstruction, predisposing athletes to a second injury and increased risk of long-term consequences.

Outcomes and Neuromuscular Changes After Anterior Cruciate Ligament Reconstructions

The most common and easiest method for assessing outcomes after ACLR is the use of patient-reported outcome measures of knee function. After ACLR, many patients report decreased quality of life and physical activity compared to healthy individuals[119,121] through the use of the International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC),[7,89] Knee Injury and Osteoarthritis Outcome

Score (KOOS),[169] and the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC).[20,21] These decreases in KOOS quality of life and IKDC scores are similar in BPTB and HG patients,[11,127,128,143] however vary by concomitant injury and sex. ACLR patients with concurrent meniscal injuries have further decreased quality of life scores compared to patients with isolated ACLR.[111] Females also report worse KOOS scores compared to male patients in pain, symptoms, sports/recreation, and quality of life for up to two years after ACLR.[3] Patients with IKDC scores below normal ranges are more likely to fail return to sport tests comprised of strength and functional tasks.[119,137]

Along with decreased quality of life and increased knee pain after ACLR, patients also demonstrate fear of returning to sport and re-injury[137,170] through the Tampa Scale of Kinesiophobia (TSK).[36,124].Patients who do not return to pre-injury level of activity have increased fear of re-injury.[108] Increased fear has also been associated with decreased knee-related quality of life.[108,170] This increased fear may affect rehabilitation adherence and outcomes by decreasing self-motivation,[31] causing a vicious cycle of decreased knee quality of life therefore increasing fear of re-injury and decreasing adherence to rehabilitation programs and preventing return to pre-injury level of activity. As many of 50% of patients who do not return to sport report a fear of re-injury.[56]

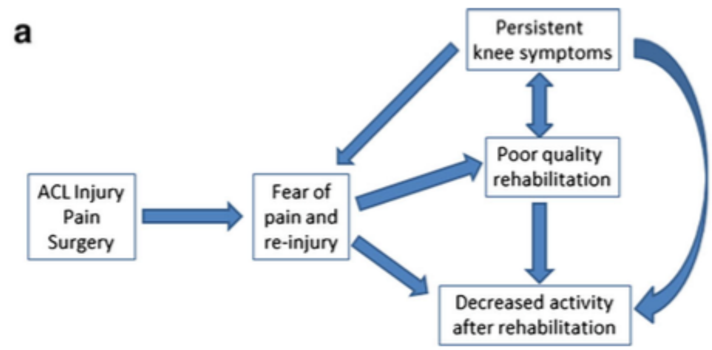


Figure B-1. The conceptual diagram of the fear-avoidance model of pain and fear of re-injury.[53]

This is a concern for sports medicine providers and orthopaedic surgeons whose goal is return patients to activity after ACLR, however less 45% return to activity or sport at 12 months post-ACLR,[81,99,172,193] and less than 30% are able to return to competitive sports 2-7 years post-ACLR.[10] Even in professional athletics, not all athletes are able to return to sport after ACLR,[51,197] and career lifespan significantly decreases after ACLR.[33,197] Some of these poor outcomes may be associated with increased kinesiophobia or may be the result of neuromuscular changes after ACLR.

The inability to return to sport has often been associated with persistent reductions in performance and deteriorated knee function after ACLR such as deficits in quadriceps activation and strength.[73,106,107,144] Patients with ACLR experience a significant decline in quadriceps strength compared to both the contralateral limb and healthy matched limb,[144,190] leading to asymmetric quadriceps strength.[91,174,208] These strength deficits in the involved limb may be from atrophied quadriceps[105] after surgical intervention causing a shift towards fatigue-resistant quadriceps[103,132,183] or may be changes in quadriceps activation.[73,144] Quadriceps activation failure is common bilaterally years after ACLR[73] even when quadriceps atrophy is no longer present.[144] Those who demonstrate better pre-operative quadriceps activation and strength have increased post-operative activation and strength,[114] as well as report better outcomes.[120] Knee extensor strength is one of the most commonly used assessments in return to play decisions.[71]

Quadriceps strength of the ACLR limb is often evaluated in comparison to the contralateral limb for a measure of limb symmetry index.[24,168] Quadriceps strength asymmetry is present after initial ACL injury and increases six months after reconstruction.[45,97] Deficits in quadriceps strength symmetry are present in both isometric and isokinetic movements.[45,74,91,97,147,175,208] Although asymmetry decreases at 9 and 12 months after reconstruction, deficits greater than 10% are still present in many individuals,[45] which is often considered low quadriceps symmetry.[147,174,208] This indicates that many patients have quadriceps strength asymmetry when they return to sport, which may increase risk of re-injury.[147,208]

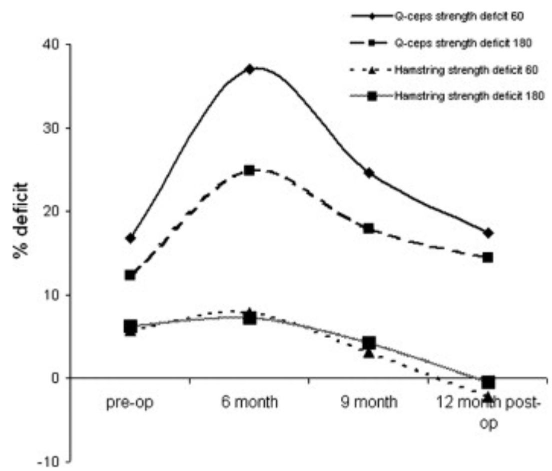


Figure B-2. Limb symmetry from time of injury until 12 months after reconstruction.[45]

Deficits in quadriceps strength can cause changes in functional tasks as well. Greater asymmetry in quadriceps strength has been associated with increased asymmetry in knee flexion excursion, peak trunk flexion angle, and peak internal knee extension moment during single leg landing.[91,147,174] Strength asymmetries also manifest in single leg hop performance,[137] with a positive correlation between isokinetic knee extensor strength and hop distance.[155] Single leg hop for distance is often used when evaluating ACLR outcomes and specifically, return to sport readiness.[2] The single leg hop test is easy to perform in the clinic and detects even small changes in performance.[68,162] The single leg hop also requires quick power development to accomplish the task and may be the most appropriate clinical task for assessing asymmetries in explosive power after

ACLR.[97] Therefore, the single leg hop is often used with patient-reported outcomes in the clinical environment to predict quadriceps strength after ACLR. This may be due to the wide range of participants in these studies considering the factors significantly associated with excellent quadriceps strength and functional performance at 6 months post-ACLR are younger age, lower body mass index, and minimal cartilage degeneration.[102] This indicates that the young athletes (<19 years old) who rupture their ACL with minimal meniscal damage have better outcomes at 6 months post-ACLR and are returned to sport. Although this is seemingly advantageous, this quick return to sport may explain the increased risk of secondary injury[83,92,171] in younger patients as well as the high percentage of osteoarthritis (OA) in men and women soccer players over a decade after an ACL injury.[121,195]

Long-term Outcomes After ACLR

Incidence of post-traumatic OA is greatest in athletes after ACLR with about 80% of men and women soccer playing showing radiographic changes in the involved knee,[121,195] however incidence of OA remains a problem for most patients after ACLR with 59% of individuals developing tibiofemoral OA and 50% developing patellofemoral OA.[43] OA of the medial compartment is three times more likely after ACLR compared to a healthy knee.[17,165] Prevalence of OA increases with concurrent meniscal injury resulting in a meniscectomy.[17,40] Many believe that BPTB grafts lead to increased prevalence of OA,[127,156] but incidence of OA after HG is equivalent.[43,185] Most alarmingly, is the increased prevalence of tibiofemoral OA after a second ACLR in the ipsilateral limb.[66] This suggests that athletes are a greater risk for developing post-traumatic OA, given how young most are at initial injury (<19 years old), therefore returning to high level sport and at increased risk of sustaining secondary injury. OA is irreversible, making it more important to properly assess athletes returning to sport to minimize risk of secondary injury. Sports medicine professionals working with youth athletes after primary ACLR should use caution when returning an athlete back to sport to minimize secondary injury and prevalence of OA.

Gait Changes After Anterior Cruciate Ligament Reconstruction

Changes in gait and loading patterns after ACLR may result in altered cartilage loading patterns and increase incidence of OA.[8,9,70,142] Patients often start walking without assistance almost immediately after ACLR,[24] however some mechanics never fully recover after ACLR. In our systematic review,[180] we compiled data from all articles reporting peak kinematics and kinetics during walking gait with a comparison to a healthy control or contralateral limb. Data were organized by group (ACLR, ACL deficient (ACLD), healthy) and limb (involved, contralateral). Weighted averages were calculated based on the sample size of each individual study at a given time since surgery. Weighted variances for each time point and group were calculated using sample sizes to generate 95% confidence intervals for each mean estimate. In the first year after ACLR, peak knee flexion angle decreases[47,54,98,167,199] while knee adduction,[200] and hip flexion angles[199] increase compared to the contralateral limb and healthy individuals. Within the 12 months after ACLR, peak external knee flexion moment,[202] knee extension moment,[202] hip flexion moment,[202] hip extension moment,[202] and knee adduction moment[200,201] are decreased compared to healthy control limbs.

Altered movement patterns at the knee remain in patients with ACLR more than three years post-surgery. Peak knee flexion angle,[140,200,201] knee adduction angle,[37,154] and knee internal rotation angle[154,198] are decreased in ACLR compared to both contralateral and healthy control limbs up to 48 months after surgery. Peak external knee extension moment,[205] knee adduction moment[176,205] and knee external rotation moment[176,205] remain reduced in ACLR compared to healthy control limbs up to 36 months after surgery. Individuals with ACLR also demonstrate increased peak knee power absorption in the uninvolved limb and those who fail return to sport criteria demonstrate increased hip power generation in the involved leg and absorb more power at the hip in the uninvolved limb.[47]

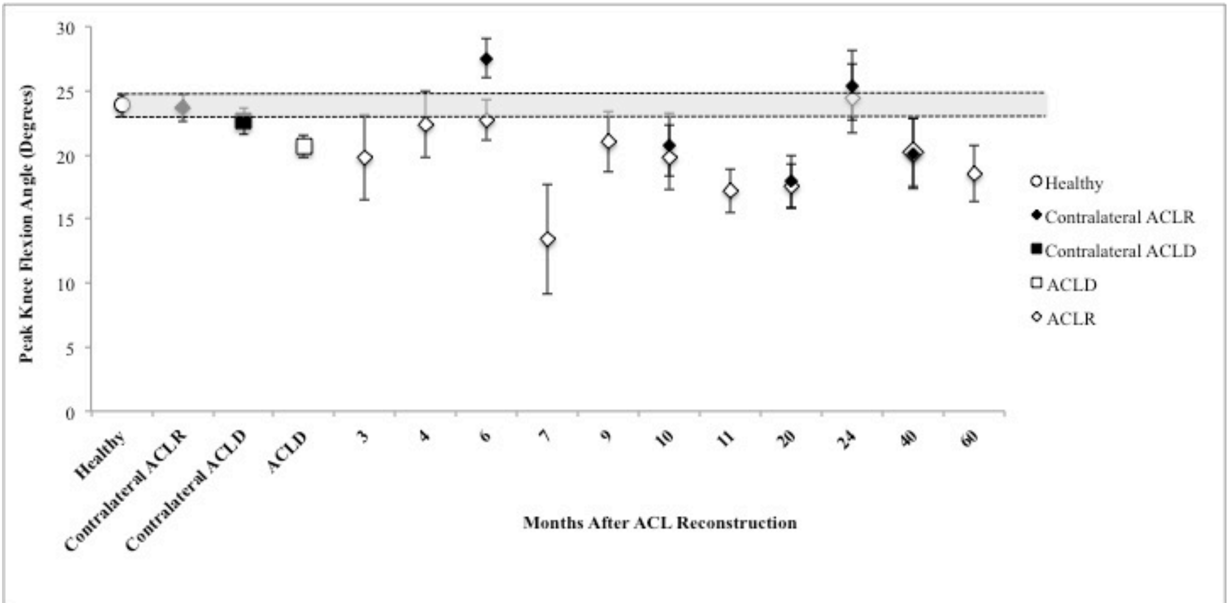


Figure B-3. Peak knee flexion angle during stance phase of walking gait for healthy individuals, contralateral anterior cruciate ligament reconstructed (ACLR) limb, contralateral anterior cruciate ligament deficient (ACLD) limb, ACLD limb, and every reported time after ACLR (months).[180]

Changes in walking gait may be due to quadriceps and hip weakness after ACLR,[44,112,113,117,190] however these changes do not resolve for more than three years after surgery. As the time since surgery increases, the frontal and sagittal plane alterations become problematic as not only a potential indicator of underlying traumatic injury risk but also as a mechanism through which knee joint cartilage degeneration may be accelerated.[72] Alterations in frontal plane kinetics and transverse plane kinematics have both been directly linked to increased cartilage loading and cartilage thinning both of which are potential signs of degeneration over time.[6,9,37,201] The continuation of tri-planar alterations in walking gait over a 3 year period following ACLR, which may account for as many as 4 million steps for the average American,[18] may have significant impact on long term joint health at long term follow-up. There are few studies that have followed up with patients greater than 36 months post-ACLR,[37,140] making it difficult to fully appreciate the progression of walking kinematics and kinetics after ACLR.

Interestingly, symmetry is often used as an indicator of acceptable muscle function[107] and movement patterns[14,52] following ACLR, however limb symmetry is largely maintained during walking gait with exception of peak knee flexion angle at 6 months post-ACLR and peak knee flexion moment at 34 months post-ACLR. This appears to be advantageous but based on the previously described differences between ACLR and healthy individuals this lack of asymmetry may indicate a negative impact of ACL injury on the contralateral limb rather than an advantageous adaptation in the involved limb. Walking gait may not be strenuous enough to illicit asymmetrical movement patterns that individuals with ACLR demonstrate in landing and strength tasks.[91,147,174]

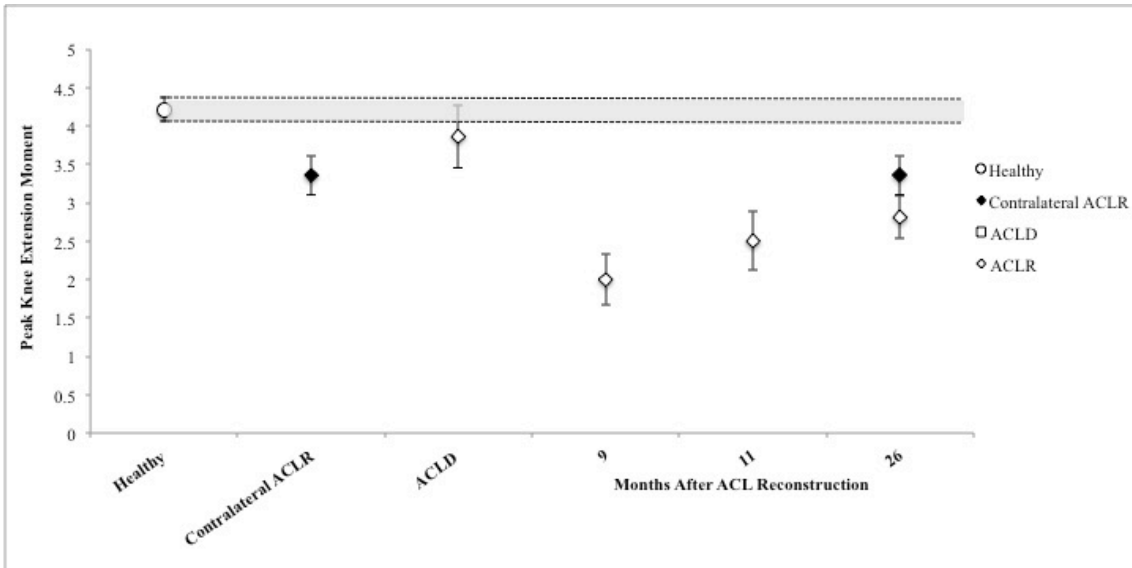


Figure B-4. Peak external knee extension moment during stance phase of walking gait for healthy individuals, contralateral anterior cruciate ligament reconstructed (ACLR) limb, anterior cruciate ligament deficient (ACLD) limb, and every reported time after ACLR (months).[180]

Unlike walking gait, there are few studies investigating differences in running gait after ACLR. Running is one of the first functional tasks patients are cleared to perform after ACLR,[178] however running gait mechanics are altered post-surgery. When cleared to return to running (approximately 4 months post-ACLR),[55] patients demonstrate decreased knee flexion during loading as well as decreased knee extensor moment impulse and negative work compared to the contralateral limb.[139,178] Patients with ACLR also demonstrate increased lateral trunk flexion towards the ipsilateral side, forward trunk lean, increased knee external rotation and knee adduction during running compared to healthy controls.[139,187] These differences indicate that loading asymmetries are present when cleared to return to running. Although rehabilitations and strengthening continues after patients return to running, alterations in running gait remain years after ACLR.

Patients with ACLR demonstrate increased impact force and loading rate while increasing hip involvement and decreasing knee torque compared to healthy controls during running.[104,140] These deviations in run gait after ACLR may be directly related to decreased knee extensor strength. Vastus lateralis activation increases in healthy limbs during high-intensity running, defined as 40% above lactate threshold, while vastus lateralis activation remained unchanged in the ACLR limb.[152,153] This impaired response to high intensity exercise may be in an effort to minimize force attenuation at the knee joint, displacing forces proximally to the hip and trunk.[104] The up regulation of hip involvement during running gait dissipates when fatigued, as patients with ACLR decrease hip flexion angle and external hip flexion moment while increasing external knee flexion moment.[104] An increased external knee flexion moment requires more eccentric work at the quadriceps to control the movement, however it is unclear the way ACLR limbs manage the eccentric load without increased activation. This is particularly important for young athletes who are exposed to fatiguing environments when returning to sport after ACLR.

Return to Activity Assessments

The most common methods currently used to evaluate return to activity readiness include patient-reported outcomes, measures of knee stability, strength testing, and the single-leg hop for distance.[71] Although patient-reported outcomes provide valuable information about strength and functional performance,[2,64,119,137,208] time from surgery remains the only criterion to return someone to unrestricted activity.[16] Most patients are returned to sport between 6-8 months after reconstruction,[16] which is concerning given the decreased quadriceps strength, quadriceps activation, and functional performance during this time period.[47,73,137,141,175,191,192] Even quadriceps strength deficits around 15% (when many are returned to sport)[16,45] alters lower extremity mechanics and explosive power which may increase risk of secondary injury.[97,147] Younger athletes tend to have better quadriceps strength and symmetry at 6 months[102] and pass return to play criteria including quadriceps strength and hop symmetry.[75,76]

It is imperative that return to play decision-making includes more sport-specific tasks when assessing an athletic population. The single-leg hop test is one of the most popular tests for assessing functional performance,[71,141,162] however the hop test is unable to predict injury and is not able to track meaningful gains in function as time from surgery increases.[79,80] Therefore, return to play decision-making should include a number of other factors other than just patient-reported outcomes and laboratory measures of functional outcomes.[42] These measures should include sport-specific outcomes[82] as well as appreciation for sport risk modifiers and decision modifiers (Figure B5). The missing variable that is not currently accounted for in decision models for return-to-play is biomechanical and muscular adaptations after exercise. Increased injury rates at the end of games indicate that neuromuscular fatigue increases risk of injury.[49,50,78] Clinicians must evaluate strength and functional movement after exercise to safely return an athlete back to sport after ACLR.

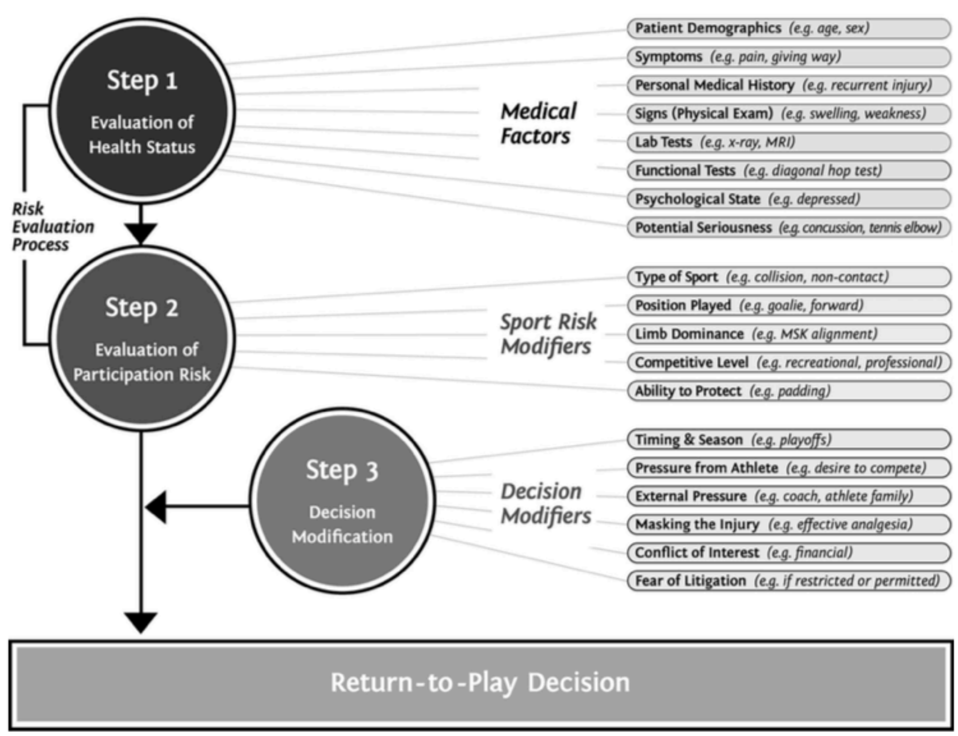


Figure B-5. Proposed return-to-play decision-making model for athletes.[42]

Applying Exercise Protocols to the Athlete Population (for assessing athlete risk)

Researchers have examined the effect of exercise on neuromuscular control and movement patterns for the past decade, however protocols differ greatly among studies. There is no accepted protocol among researchers, leading different laboratories to design different fatigue protocol dependent on participant level of fitness and measures of interest. This discrepancy between exercise protocols makes it difficult to compare results and few of these protocols apply to the fatigue experienced by elite athletes during training and competition.

Many of the exercise protocols used to induce neuromuscular fatigue in the 1980s and 1990s included repetitive dynamic knee extensor exercises or weighted squats until exhaustion and these designs are still utilized today.[15,61,77,122,145,189] Some of the most popular protocols require controlled, repetitive movements until the participant can no longer complete the task at the preselected speed.[115,145] These protocols may produce knee extensor fatigue, however the controlled uniplanar nature of the exercises limits applicability and may explain reported minimal changes after exercise using these protocols compared to other exercises.[115] Other protocols utilize a combination of anaerobic exercises, such as squat jumps and short sprints,[39,123] or single leg landings and squats[41] to induce fatigue using exercises that simulate movements experienced during sport and activity. Graded treadmill exercise has been used previously to test cardiopulmonary fitness,[1,204] however has been used for knee rehabilitation because it increases quadriceps activation[110] and is a popular choice to induce neuromuscular fatigue.[38,44,103] These types of aerobic protocols are not applicable to sporting environments that require both high-intensity aerobic and anaerobic components.[163]

Athletes vs. Non-athletes

Exercise used to induce neuromuscular fatigue should be different based on training status to account for differences in training level. Highly trained individuals have improved aerobic fitness, strength, and power compared to recreationally active individuals.[62,136,163,207] A highly trained individual has a lower heart rate during exhaustive exercise[35] takes longer to fatigue than a recreationally active individual.[116] This is likely due to high-level athletes being exposed to environments that induce both peripheral and central fatigue on a regular basis, resulting in increased fitness and recovery time.[13,90,101,161] High-level athletes are at increased risk of knee injury[23] and are more likely to incur a second injury during a game[4,5,63,86] after being returned to sport.[83,92,95,203] Therefore, we need to model sport when assessing exercise-related adaptations that increase risk of secondary injury in athletes after ACLR.

Modeling Sport

The first exercise protocols that mimicked actual soccer play incorporated a series of step-up and plyometric movements with direction changes for four minutes[133] or repetitive jumps over obstacles with maximal vertical jumps.[148] These exercise protocols predominantly simulate the anaerobic demands of sport without incorporating the cardiovascular demands. Other protocols only simulate the cardiovascular demands of competitive soccer without including changes of direction. Aerobic exercise results in decreases in knee extensor strength, which may contribute to risk of injury when fatigued however few knee injuries occur during straight-line exercises.[159]

There are a few currently used exercise protocols that combine the anaerobic and aerobic demands of competitive soccer to induce sport-specific neuromuscular fatigue.[126,138,177,181] All these protocols include approximately 90 minutes of exercise to exactly model the length of soccer matches and two protocols were developed using time motion analyses in professional soccer matches. These protocols are data-driven and certainly more applicable to the athlete population, however overestimate the relative time spent walking (Table B-1).[29,196]

Table B-1. Review of literature of relative time spent standing, walking, jogging, running, and sprinting during a 90-minute soccer game.

	N_{Total}	Standing	Walking	Jogging	Running	High-Speed Running	Sprinting
Krustrup et al[101]	14	16%	44%	34%	4.8%	-	1.55%
Mohr et al[134]	18	18.95%	42.7%	17.9%	13.6%	2.35%	0.90%
Magalhaes et al[126]	16	7.8%	43.8%	35.03%	5.8%	-	2.5%
Bradley et al[30]	370	5.6%	59.4%	26.1%	6.4%	2.0%	0.60%
Bradley et al[29]	711	-	33.02%	40.26%	17.02%	6.99%	2.7%
Vescovi et al[196]	113	-	29.35%	12.01%	46.19%	9.02%	3.29%
Slater et al[179]	22	-	19.96%	36.64%	25.37%	12.26%	5.76%

Furthermore, these distributions are largely representative of professional male soccer players as opposed to youth and college soccer players who are exposed to different demands that professional athletes. In comparison to the professional male players, collegiate players spend less time walking and jogging during a soccer game, and more relative time running and sprinting (Figure B-6).[196] There is a need for a laboratory-based exercise protocol that models the demands of amateur soccer including unanticipated changes of direction. Given the nature of the sport, it can be assumed that most of the 5,000 turning events during a soccer game[25] are in response to movement on the field and require some level of decision-making.[118,166] Furthermore, athletes display altered kinematics and muscle recruitment strategy during unanticipated maneuvers in a fatigued state, indicating that injury risk may increase with neuromuscular and cognitive fatigue.[19,28,173]

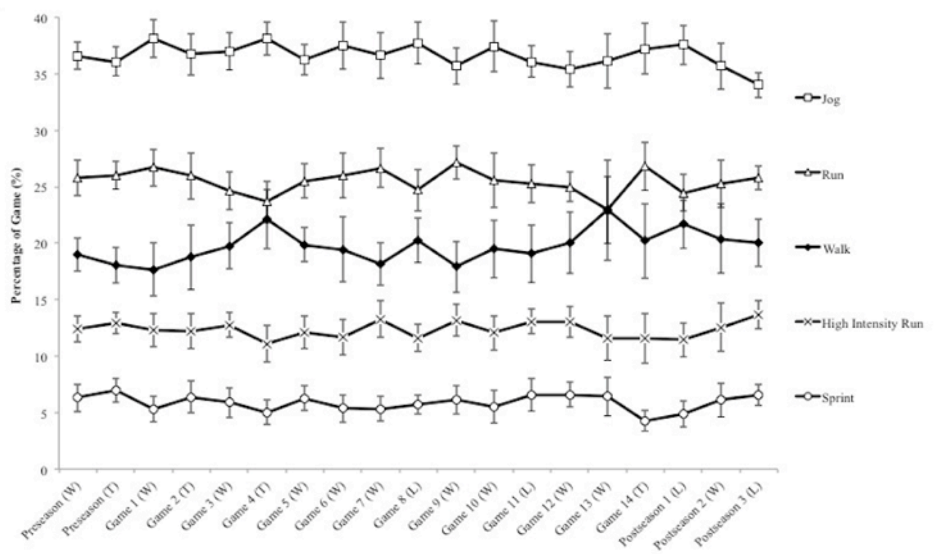


Figure B-6. Average percent of game spent walking, jogging, running, high intensity running, and sprinting with 95% confidence intervals. Wins (W), losses (L), and ties (T) are noted next to each game.[179]

After Prolonged Exercise

Modeling these sport-specific demands are important to appreciate adaptations due to neuromuscular fatigue that may increase risk of injuries at the end of soccer games.[49,50,78] Healthy individuals demonstrate stiffer landings with increased knee laxity after soccer-specific exercise,[177] which may be the result of decreased functional hamstring to quadriceps ratio when fatigued.[181] Gait patterns also change in healthy individuals when fatigued,[104,158] however there is little information regarding biomechanical adaptations in patients with ACLR when fatigued. Patients with ACLR demonstrate different adaptations to neuromuscular fatigue. Healthy individuals demonstrate significant declines in knee extensor strength and activation after exercise while individuals with ACLR demonstrate a much smaller decline after exercise.[103,189] Patients with ACLR however exhibit greater reductions in hip extensor strength after exercise compared to healthy controls, which may be the result from increased hip involvement when rested causing the hip musculature to fatigue quickly.[44,104] After soccer-specific exercise, individuals with ACLR also demonstrate increased vertical ground reaction forces during landing, particularly in the anterior-posterior direction, possibly due to decreased dynamic balance.[44,149]

Clinical Implications

These neuromuscular adaptations when fatigued after ACLR indicate that young athletes who pass return to play clinical testing in a rested state may still be at risk for a secondary injury when exposed to a fatiguing athletic environment. There is a need for further research investigating biomechanical adaptations in athletes with ACLR fatigue after sport-specific exercise when cleared to return to high level of activity. This will guide return to play decision making for younger athletes with ACLR who are at increased risk for sustaining a second ACL injury and development of post-traumatic OA.

Conclusion

Athletes under 19 years old, specifically in soccer and basketball, are at increased risk for ACL injury.[4,23,86,194] After ACLR, these young athletes have better functional and patient-reported outcomes six months after surgery and are returned to sport. This quick return to sport may explain the increased risk of secondary injury in younger patients as well as the high percentage of OA in soccer players after ACLR. Although these athletes are motivated to return to sport and have better strength and function after ACLR, clinicians predominantly test these patients in a rested state. A better appreciation for biomechanical adaptations in this high-risk population during a sport-specific fatigued state may guide return to play decision-making to minimize risk of secondary injury and long-term consequences after ACLR.

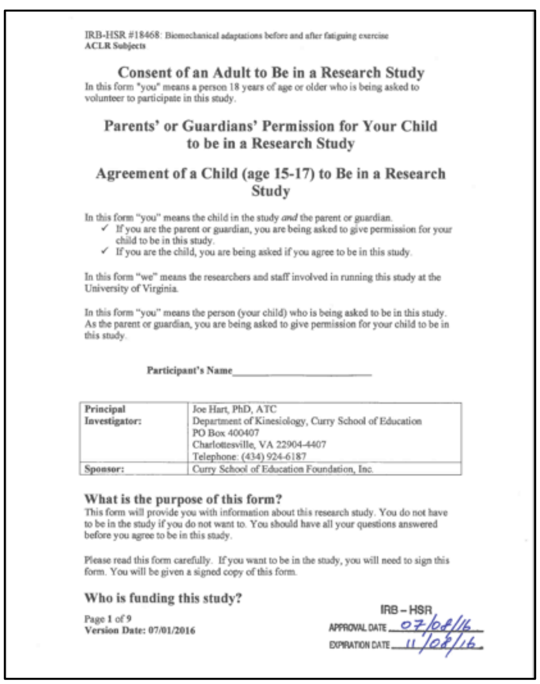
APPENDIX C

Additional Methods

Table C-1. Overall Study Procedures

1. Visit 1: Strength and Maximal Treadmill Testing
   a. Informed Consent
   b. Review Eligibility Criteria
   c. Participant Questionnaires
   d. Isokinetic and Isometric Knee Extensor and Flexor Strength Testing
   e. Single Hop for Distance Testing
   f. Maximal Treadmill Testing
2. Visit 2: Exercise Session 1
   a. Motion Capture: Walking and Running
   b. Exercise for 30 minutes
   c. Motion Capture: Walking and Running
3. Visit 3: Exercise Session 2
   a. Motion Capture: Walking and Running
   b. Exercise for 30 minutes
   c. Motion Capture: Walking and Running

Table C-2. Informed Consent Form



IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

Consent of an Adult to Be in a Research Study

In this form "you" means a person 18 years of age or older who is being asked to volunteer to participate in this study.

Parents' or Guardians' Permission for Your Child to be in a Research Study

Agreement of a Child (age 15-17) to Be in a Research Study

In this form "you" means the child in the study *and* the parent or guardian.
- ✓ If you are the parent or guardian, you are being asked to give permission for your child to be in this study.
- ✓ If you are the child, you are being asked if you agree to be in this study.

In this form "we" means the researchers and staff involved in running this study at the University of Virginia.

In this form "you" means the person (your child) who is being asked to be in this study. As the parent or guardian, you are being asked to give permission for your child to be in this study.

Participant's Name____________________

Principal Investigator:	Joe Hart, PhD, ATC Department of Kinesiology, Curry School of Education PO Box 400407 Charlottesville, VA 22904-4407 Telephone: (434) 924-6187
Sponsor:	Curry School of Education Foundation, Inc.

What is the purpose of this form?

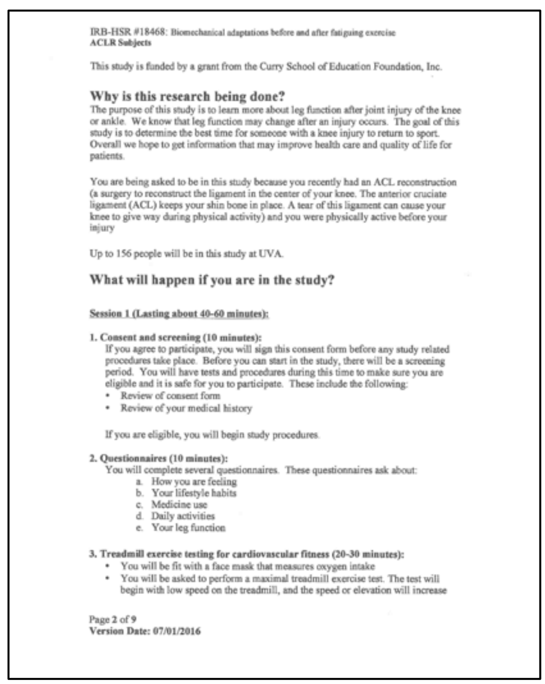
This form will provide you with information about this research study. You do not have to be in the study if you do not want to. You should have all your questions answered before you agree to be in this study.

Please read this form carefully. If you want to be in the study, you will need to sign this form. You will be given a signed copy of this form.

Who is funding this study?

Page 1 of 9
Version Date: 07/01/2016

IRB – HSR
APPROVAL DATE 07/08/16
EXPIRATION DATE 11/08/16



IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

This study is funded by a grant from the Curry School of Education Foundation, Inc.

Why is this research being done?

The purpose of this study is to learn more about leg function after joint injury of the knee or ankle. We know that leg function may change after an injury occurs. The goal of this study is to determine the best time for someone with a knee injury to return to sport. Overall we hope to get information that may improve health care and quality of life for patients.

You are being asked to be in this study because you recently had an ACL reconstruction (a surgery to reconstruct the ligament in the center of your knee. The anterior cruciate ligament (ACL) keeps your shin bone in place. A tear of this ligament can cause your knee to give way during physical activity) and you were physically active before your injury

Up to 156 people will be in this study at UVA.

What will happen if you are in the study?

Session 1 (Lasting about 40-60 minutes):

1. Consent and screening (10 minutes):
If you agree to participate, you will sign this consent form before any study related procedures take place. Before you can start in the study, there will be a screening period. You will have tests and procedures during this time to make sure you are eligible and it is safe for you to participate. These include the following:
- Review of consent form
- Review of your medical history

If you are eligible, you will begin study procedures.

2. Questionnaires (10 minutes):
You will complete several questionnaires. These questionnaires ask about:
a. How you are feeling
b. Your lifestyle habits
c. Medicine use
d. Daily activities
e. Your leg function

3. Treadmill exercise testing for cardiovascular fitness (20-30 minutes):
- You will be fit with a face mask that measures oxygen intake
- You will be asked to perform a maximal treadmill exercise test. The test will begin with low speed on the treadmill, and the speed or elevation will increase

Page 2 of 9
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

gradually every 2 minutes. You will be asked to go as long as you can until you feel exhausted.

Session 2 (Lasting about 60-90 minutes):

- You will be asked to complete 3 maximal vertical jumps for height before and after exercise
- You will be asked to complete a hopping task for time before and after exercise
- We will apply the motion capture sensors and EMG sensors to your lower body – they will be placed on your feet, calves, thighs and back. The skin where these sensors will be placed may need to be shaved of hair and exfoliated (lightly rub with a rough surface and cleaned with rubbing alcohol).
- You will be fit with a heart rate monitor for the duration of the study visit.
- You will be asked to complete an exercise protocol including treadmill walking (less than 7.2 km/h), treadmill jogging (greater than 7.2 km/h), and treadmill running (greater than 10.1 km/h) and agility exercises on a gym floor including changes of direction, lateral jumping, hopping and squat jumps. All walking, jogging, and running will be completed in brief intervals lasting 20 seconds to 3 minutes.
- During the movements, we will record the muscle activity of your leg and trunk using electromyography (EMG). EMG involves placing electrodes, similar to a sticker, over your muscle and leg to see how much the muscle is being used.
- We will also use a computer to record your body motions during your movements.

How long will this study take?
This study will require two visits over 3 weeks. Each visit will last about 30-90 minutes.

If you want to know about the results before the study is done:
During the study your study leader will let you know of any test results that may be important to your health. In addition, as the research moves forward, your study leader will keep you informed of any new findings that may be important for your health or may help you decide if you want to continue in the study. The final results of the research will not be known until all the information from everyone is combined and reviewed. At that time you can ask for more information about the study results.

What are the risks of being in this study?

Risks and side effects related include:

- You may have temporary skin irritation from EMG or motion capture skin preparation.
- You may experience muscle soreness from the exercise protocols.
- You may experience a lower extremity joint sprain, such as ankle or knee from the exercise protocols.

Page **3** of **9**
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

- You may faint or experience chest pain from maximal treadmill testing.

There are no known serious side effects associated with the tests and procedures in this study. The unlikely occurrence of the low risk side effects listed above should resolve with no complications.

Could you be helped by being in this study?
You will not benefit from being in this study. However the information researchers get from this study may help others in the future.

What are your other choices if you do not join this study?
The only choice is not to be in this study.

Will you be paid for being in this study?
You will be paid $5 for completion of the first session and $15 for completion of the second session by **check**. You will be paid **$20** for finishing this study by **check**.

You should get your payment about **2-6 weeks** after each study visit. The income may be reported to the IRB as income.

You will not be paid at all if **you** decide not to finish this study. If the study leader says you cannot continue, you will be paid the full amount of the study.

If you owe money to the University of Virginia or the University of Virginia Medical Center, the money to be paid to you in this study can be withheld to pay what you owe. And if a court has issued a judgment against you, the money may also be withheld to pay the judgment creditor for such things as taxes, fines, or child support that you owe.

Will being in this study cost you any money?
All of the procedures in this study will be provided at no cost to you or your health insurance. You will be responsible for the cost of travel to come to any study visit and for any parking costs.

What if you are hurt in this study?
If you are hurt as a result of being in this study, there are no plans to pay you for medical expenses, lost wages, disability, or discomfort. The charges for any medical treatment you receive will be billed to your insurance. You will be responsible for any amount your insurance does not cover. You do not give up any legal rights, such as seeking compensation for injury, by signing this form.

What happens if you leave the study early?
You can change your mind about being in the study any time. You can agree to be in the study now and change your mind later. If you decide to stop, please tell us right away.

Page **4** of **9**
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

You do not have to be in this study to get services you can normally get at the University of Virginia.

Even if you do not change your mind, the study leader (Dr. Joe Hart) can take you out of the study.

How will your personal information be shared?
The UVa researchers are asking for your permission to gather, use and share information about you for this study. If you decide not to give your permission, you cannot be in this study, but you can continue to receive regular medical care at UVA.

If you sign this form, we may collect any or all of the following information about you:

- Personal information such as name, address and date of birth
- Social Security number only if you are being paid to be in this study
- Your health information if required for this study. This may include a review of your medical records and test results from before, during and after the study from any of your doctors or health care providers.

Who will see your private information?

- The researchers to make sure they can conduct the study the right way, observe the effects of the study and understand its results
- People or groups that oversee the study to make sure it is done correctly
- The sponsor(s) of this study, and the people or groups it hires to help perform or review this research
- Insurance companies or other organizations that may need the information in order to pay your medical bills or other costs of your participation in the study
- Tax reporting offices (if you are paid for being in the study)
- People who evaluate study results, which can include sponsors and other companies that make the drug or device being studied, researchers at other sites conducting the same study, and government agencies that provide oversight such as the Food and Drug Administration (FDA) if the study is regulated by the FDA.

Some of the people outside of UVa who will see your information may not have to follow the same privacy laws that we follow. They may release your information to others, and it may no longer be protected by those laws.

The information collected from you might be published in a medical journal. This would be done in a way that protects your privacy. No one will be able to find out from the article that you were in the study.

What if you sign the form but then decide you don't want your private information shared?
You can change your mind at any time. Your permission does not end unless you cancel it. To cancel it, please send a letter to the researchers listed on this form. Then you will

Page **5** of **9**
Version *Date:* 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

no longer be in the study. The researchers will still use information about you that was collected before you ended your participation.

Please contact the researchers listed below to:

- Obtain more information about the study
- Ask a question about the study procedures or treatments
- Report an illness, injury, or other problem (you may also need to tell your regular doctors)
- Leave the study before it is finished
- Express a concern about the study

Joe Hart, PhD, ATC
Human Services, Curry School of Education
PO Box 400407
Charlottesville, VA 22904-4407
Telephone: (434) 924-6187

What if you have a concern about this study?
You may also report a concern about this study or ask questions about your rights as a research subject by contacting the Institutional Review Board listed below.

University of Virginia Institutional Review Board for Health Sciences Research
PO Box 800483
Charlottesville, Virginia 22908

Telephone: 434-924-9634

When you call or write about a concern, please give as much information as you can. Include the name of the study leader, the IRB-HSR Number (at the top of this form), and details about the problem. This will help officials look into your concern. When reporting a concern, you do not have to give your name.

Signatures
What does your signature mean?
Before you sign this form, please ask questions about any part of this study that is not clear to you. Your signature below means that you have received this information and all your questions have been answered. If you sign the form it means that you agree to join the study. You will receive a copy of this signed document.

Consent From Adult

______________	______________	______
PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

Page **6** of **9**
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

To be completed by participant if 18 years of age or older.

If an interpreter is involved in the consent process because the potential subject does not speak English well or at all, the participant should NOT sign on the line above – leave this line blank. Instead, the participant should sign the Short Form or full consent written in the language they can understand.

Person Obtaining Consent
By signing below you confirm that you have fully explained this study to the potential subject, allowed them time to read the consent or have the consent read to them, and have answered all their questions.

PERSON OBTAINING CONSENT (SIGNATURE)	PERSON OBTAINING CONSENT (PRINT)	DATE

Consent from Impartial Witness
If this consent form is read to the subject because the subject is blind or illiterate, an impartial witness not affiliated with the research or study doctor must be present for the consenting process and sign the following statement. The subject may place an X on the Participant Signature line above.

I agree the information in this informed consent form was presented orally in my presence to the **identified individual(s)** who has had the opportunity to ask any questions he/she had about the study. I also agree that the **identified individual(s)** freely gave their informed consent to participate in this trial.

IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Parental/ Guardian Permission
By signing below you confirm you have the legal authority to sign for this child.

PARENT/GUARDIAN (SIGNATURE)	PARENT/GUARDIAN (PRINT NAME)	DATE

Page 7 of 9
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

Person Obtaining Parental/Guardian Permission
By signing below you confirm that you have fully explained this study to the parent/guardian, allowed them time to read the consent or have the consent read to them, and have answered all their questions.

PERSON OBTAINING PARENTAL/ GUARDIAN PERMISSION (SIGNATURE)	PERSON OBTAINING PARENTAL/GUARDIAN PERMISSION (PRINT NAME)	DATE

Consent From Impartial Witness
If this consent form is read to the parent(s) because the parent(s) is blind or illiterate, an impartial witness not affiliated with the research or study doctor must be present for the consenting process and sign the following statement. The parent may place an X on the Parent Signature line above.

I agree the information in this informed consent form was presented orally in my presence to the parent(s) guardian(s) and the parent(s)/guardian(s) had the opportunity to ask any questions he/she had about the study. I also agree that the parent(s)/guardian(s) freely gave their informed consent for their child to participate in this trial.

IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Assent from Child
Consent from the parent/guardian MUST be obtained before approaching the child for their assent.

PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

Person Obtaining Assent of the Child (less than 18 years of age)
Consent from the parent/guardian MUST be obtained before approaching the child for their assent.

Page 8 of 9
Version Date: 07/01/2016

IRB-HSR #18468: Biomechanical adaptations before and after fatiguing exercise
ACLR Subjects

By signing below you confirm that the study has been explained to the child (less than 18 years of age), all questions have been answered and the child has voluntarily agreed to participate.

PERSON OBTAINING ASSENT (SIGNATURE)	PERSON OBTAINING ASSENT (PRINT)	DATE

Page 9 of 9
Version Date: 07/01/2016

Table C-3. Health History Form

General Health History Form
UVA Exercise and Sports Injury Laboratory

Name: ____________________
Date of Visit: _______________

Height	Weight	Sex	Age	Date of Birth
				/ /

Please check below if you have had any of the following and explain checked items on line.

General Medical

☐ Allergies/Sensitivies (latex, cold, medications, etc.)
☐ Asthma
☐ Cancer
☐ Biomedical devices (implants, pacemaker, etc.)
☐ Diabetes
☐ Pregnant or nursing
☐ Recent illness (cold, flu, infection, etc.)
☐ Surgery
☐ Other: ______________

Please Explain: ____

Neurological

☐ Epilepsy/Seizures
☐ Anxiety disorder
☐ ADHD
☐ Diabetic neuropathy
☐ Multiple Sclerosis
☐ Parkinson disease
☐ Cerebral Palsy
☐ Vertigo
☐ Balance disorder
☐ Concussion or Traumatic brain injury
☐ Other: ______________

Please Explain: ____

Cardiovascular

☐ High blood pressure
☐ Shortness of breath
☐ Heart attack
☐ Heart disease
☐ Stroke
☐ Heart murmur
☐ Thrombosis or Embolism
☐ Marfan's Syndrome
☐ Sickle cell trait
☐ Cardiac Arrhythmia (irregular heart beat)
☐ Other: ______________

Please Explain: ____

General Orthopaedic

☐ Surgery
☐ Previous fracture
☐ Sprains or Strains (ligament/muscle/tendon)
☐ Osteoarthritis
☐ Rheumatoid arthritis
☐ Assistive devices (crutches, braces, etc.)
☐ Gout
☐ Osteoporosis/Osteopenia
☐ Other: ______________

Please Explain: ____

Other

❖ Have you taken any prescription or over-the-counter medications within the last 24-hours?
☐ YES ☐ NO *If yes, please list:* ______________________________

❖ Have you consumed any of the following stimulants or depressants in the last 12-hours?
☐ Caffeine ☐ Alcohol ☐ Tobacco
If yes, please explain: ______________________________

❖ Do you exercise regularly? ☐ YES ☐ NO
If yes, what type and for how long? ______________________________

❖ Are you currently experiencing physical pain? ☐ YES ☐ NO
If yes, please indicate location, severity, and currently treatments for you pain:
____

Table C-4. International Knee Documentation Committee (IKDC) Subjective Knee Evaluation[7]

2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

Today's Date: ____/____/____ (Day / Month / Year) Date of Injury: ____/____/____ (Day / Month / Year)

SYMPTOMS*:

*Grade symptoms at the highest activity level at which you think you could function without significant symptoms, even if you are not actually performing activities at this level.

1. What is the highest level of activity that you can perform without significant knee pain?

   ☐ Very strenuous activities like jumping or pivoting as in basketball or soccer
   ☐ Strenuous activities like heavy physical work, skiing or tennis
   ☐ Moderate activities like moderate physical work, running or jogging
   ☐ Light activities like walking, housework or yard work
   ☐ Unable to perform any of the above activities due to knee pain

2. During the past 4 weeks, or since your injury, how often have you had pain?

	10	9	8	7	6	5	4	3	2	1	0	
Never	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Constant

3. If you have pain, how severe is it?

	10	9	8	7	6	5	4	3	2	1	0	
No pain	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Worst pain imaginable

4. During the past 4 weeks, or since your injury, how stiff or swollen was your knee?

   ☐ Not at all
   ☐ Mildly
   ☐ Moderately
   ☐ Very
   ☐ Extremely

5. What is the highest level of activity you can perform without significant swelling in your knee?

   ☐ Very strenuous activities like jumping or pivoting as in basketball or soccer
   ☐ Strenuous activities like heavy physical work, skiing or tennis
   ☐ Moderate activities like moderate physical work, running or jogging
   ☐ Light activities like walking, housework, or yard work
   ☐ Unable to perform any of the above activities due to knee swelling

6. During the past 4 weeks, or since your injury, did your knee lock or catch?

   ☐ Yes ☐ No

7. What is the highest level of activity you can perform without significant giving way in your knee?

   ☐ Very strenuous activities like jumping or pivoting as in basketball or soccer
   ☐ Strenuous activities like heavy physical work, skiing or tennis
   ☐ Moderate activities like moderate physical work, running or jogging
   ☐ Light activities like walking, housework or yard work
   ☐ Unable to perform any of the above activities due to giving way of the knee

Page 2 – 2000 IKDC SUBJECTIVE KNEE EVALUATION FORM

SPORTS ACTIVITIES:

8. What is the highest level of activity you can participate in on a regular basis?

   ☐ Very strenuous activities like jumping or pivoting as in basketball or soccer
   ☐ Strenuous activities like heavy physical work, skiing or tennis
   ☐ Moderate activities like moderate physical work, running or jogging
   ☐ Light activities like walking, housework or yard work
   ☐ Unable to perform any of the above activities due to knee

9. How does your knee affect your ability to:

	Not difficult at all	Minimally difficult	Moderately Difficult	Extremely difficult	Unable to do
a. Go up stairs	☐	☐	☐	☐	☐
b. Go down stairs	☐	☐	☐	☐	☐
c. Kneel on the front of your knee	☐	☐	☐	☐	☐
d. Squat	☐	☐	☐	☐	☐
e. Sit with your knee bent	☐	☐	☐	☐	☐
f. Rise from a chair	☐	☐	☐	☐	☐
g. Run straight ahead	☐	☐	☐	☐	☐
h. Jump and land on your involved leg	☐	☐	☐	☐	☐
i. Stop and start quickly	☐	☐	☐	☐	☐

FUNCTION:

10. How would you rate the function of your knee on a scale of 0 to 10 with 10 being normal, excellent function and 0 being the inability to perform any of your usual daily activities which may include sports?

FUNCTION PRIOR TO YOUR KNEE INJURY:

	0	1	2	3	4	5	6	7	8	9	10	
Couldn't perform daily activities	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	No limitation in daily activities

CURRENT FUNCTION OF YOUR KNEE:

	0	1	2	3	4	5	6	7	8	9	10	
Cannot perform daily activities	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	No limitation in daily activities

Table C-5. Knee Injury and Osteoarthritis Outcome Score (KOOS)[169]

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 1

KOOS KNEE SURVEY

Today's date: _____/_____/_____ Date of birth: _____/_____/_____

Name: ____

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

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

S1. Do you have swelling in your knee?
Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always ☐

S2. Do you feel grinding, hear clicking or any other type of noise when your knee moves?
Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always ☐

S3. Does your knee catch or hang up when moving?
Never ☐ Rarely ☐ Sometimes ☐ Often ☐ Always ☐

S4. Can you straighten your knee fully?
Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never ☐

S5. Can you bend your knee fully?
Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never ☐

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

S6. How severe is your knee joint stiffness after first wakening in the morning?
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

S7. How severe is your knee stiffness after sitting, lying or resting **later in the day**?
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 2

Pain
P1. How often do you experience knee pain?
Never ☐ Monthly ☐ Weekly ☐ Daily ☐ Always ☐

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

P2. Twisting/pivoting on your knee
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P3. Straightening knee fully
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P4. Bending knee fully
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P5. Walking on flat surface
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P6. Going up or down stairs
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P7. At night while in bed
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P8. Sitting or lying
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

P9. Standing upright
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

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

A1. Descending stairs
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A2. Ascending stairs
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 3

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A3. Rising from sitting
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A4. Standing
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A5. Bending to floor/pick up an object
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A6. Walking on flat surface
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A7. Getting in/out of car
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A8. Going shopping
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A9. Putting on socks/stockings
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A10. Rising from bed
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A11. Taking off socks/stockings
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A12. Lying in bed (turning over, maintaining knee position)
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A13. Getting in/out of bath
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A14. Sitting
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A15. Getting on/off toilet
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Knee injury and Osteoarthritis Outcome Score (KOOS), English version LK1.0 4

For each of the following activities please indicate the degree of difficulty you have experienced in the **last week** due to your knee.

A16. Heavy domestic duties (moving heavy boxes, scrubbing floors, etc)
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

A17. Light domestic duties (cooking, dusting, etc)
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

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

SP1. Squatting
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP2. Running
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP3. Jumping
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP4. Twisting/pivoting on your injured knee
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

SP5. Kneeling
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

Quality of Life
Q1. How often are you aware of your knee problem?
Never ☐ Monthly ☐ Weekly ☐ Daily ☐ Constantly ☐

Q2. Have you modified your life style to avoid potentially damaging activities to your knee?
Not at all ☐ Mildly ☐ Moderately ☐ Severely ☐ Totally ☐

Q3. How much are you troubled with lack of confidence in your knee?
Not at all ☐ Mildly ☐ Moderately ☐ Severely ☐ Extremely ☐

Q4. In general, how much difficulty do you have with your knee?
None ☐ Mild ☐ Moderate ☐ Severe ☐ Extreme ☐

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

Table C-6. Godin Leisure-Time Exercise Questionnaire[65]

Godin Leisure-Time Exercise Questionnaire

1. During a typical **7-Day period** (a week), how many times on the average do you do the following kinds of exercise for **more than 15 minutes** during your free time (write on each line the appropriate number).

	Times Per Week
a) **STRENUOUS EXERCISE (HEART BEATS RAPIDLY)** (e.g., running, jogging, hockey, football, soccer, squash, basketball, cross country skiing, judo, roller skating, vigorous swimming, vigorous long distance bicycling)	_____
b) **MODERATE EXERCISE (NOT EXHAUSTING)** (e.g., fast walking, baseball, tennis, easy bicycling, volleyball, badminton, easy swimming, alpine skiing, popular and folk dancing)	_____
c) **MILD EXERCISE (MINIMAL EFFORT)** (e.g., yoga, archery, fishing from river bank, bowling, horseshoes, golf, snow-mobiling, easy walking)	_____

2. During a typical **7-Day period** (a week), in your **leisure** time, how often do you engage in any regular activity **long enough to work up a sweat** (heart beats rapidly)?

OFTEN	SOMETIMES	NEVER/RARELY
1. ☐	2. ☐	3. ☐

Table C-7. Marx Activity Scale[131]

MARX SCALE (ENGLISH VERSION)

Please indicate how often you performed each activity in your healthiest and most active state, in the past year. Kindly put a (☑) mark on the appropriate space after each item.

	Less than one time in a month	One time in a month	One time in a week	2 or 3 times in a week	4 or more times in a week
Running: running while playing a sport or jogging	0	1	2	3	4
Cutting: changing directions while running	0	1	2	3	4
Deceleration: coming to a quick stop while running	0	1	2	3	4
Pivoting: turning your body with your foot planted while playing sport; For example: skiing, skating, kicking, throwing, hitting a ball (golf, tennis, squash), etc.	0	1	2	3	4

C-8. Tegner Activity Scale[188]

TEGNER ACTIVITY SCALE

Please indicate in the spaces below the HIGHEST level of activity that you participated in BEFORE YOUR INJURY and the highest level you are able to participate in CURRENTLY.

BEFORE INJURY: Level__________ CURRENT: Level__________

Level 10	Competitive sports- soccer, football, rugby (national elite)
Level 9	Competitive sports- soccer, football, rugby (lower divisions), ice hockey, wrestling, gymnastics, basketball
Level 8	Competitive sports- racquetball or bandy, squash or badminton, track and field athletics (jumping, etc.), down-hill skiing
Level 7	Competitive sports- tennis, running, motorcars speedway, handball Recreational sports- soccer, football, rugby, bandy, ice hockey, basketball, squash, racquetball, running
Level 6	Recreational sports- tennis and badminton, handball, racquetball, down-hill skiing, jogging at least 5 times per week
Level 5	Work- heavy labor (construction, etc.) Competitive sports- cycling, cross-country skiing, Recreational sports- jogging on uneven ground at least twice weekly
Level 4	Work- moderately heavy labor (e.g. truck driving, etc.)
Level 3	Work- light labor (nursing, etc.)
Level 2	Work- light labor Walking on uneven ground possible, but impossible to back pack or hike
Level 1	Work- sedentary (secretarial, etc.)
Level 0	Sick leave or disability pension because of knee problems

All information in this Worksheet is **Confidential**.

C-9. Visual Analog Scale for Soreness

VISUAL ANALOG SCALE:
Place a vertical mark or 'X' on the line below that best represents your knee pain ***DURING A SINGLE-LEG SQUAT***

Right

No Pain ________________________________ Worst possible pain

Rating: ____________ cm

Left

No Pain ________________________________ Worst possible pain

Rating: ____________ cm

VISUAL ANALOG SCALE:
Place a vertical mark or 'X' on the line below that best represents your ***muscle soreness***:

Right

No Soreness ________________________________ Worst possible soreness

Rating: ____________ cm

Left

No Soreness ________________________________ Worst possible soreness

Rating: ____________ cm

Did muscle soreness prevent you from performing your usual activities (including work, school or housework) in the past day?

☐ No interference ☐ Mild interference ☐ Moderate interference ☐ Extreme interference

Did muscle soreness prevent you from performing any recreational, social, family, or sporting activities in the past day?

☐ No interference ☐ Mild interference ☐ Moderate interference ☐ Extreme interference

C-10. Data Collection Forms

Screening Visit:

Age: ______ Height:________ Weight:________ BMI:_________=[(lbs/in^2)/703]

Date of Birth: ____________ Date of Surgery: ______________

Graft Type: ____

Concomitant Injury: ____

Injury History: ____

____

____

____

____

LEAP Subject Number: ___________________

Gender: ☐Male
☐Female

Race: ☐American Indian / Alaskan Native
☐White
☐Black/African American
☐Native Hawaiian/ Other Pacific Islander
☐Asian
☐Other (Specify)________________________________

Ethnicity ☐ Hispanic / Latino
☐ Non Hispanic/ Latino

Sport: ☐Football
☐Basketball
☐Soccer
☐Lacrosse
☐Baseball/Softball
☐Field Hockey
☐Volleyball
☐Other (Specify)________________________________
☐Recreational Athlete

If Multi-Sport Athlete, Main Sport: ______________________________

Inclusion Criteria

☐ YES	☐ NO	Age at time of randomization: 15-40 years
☐ YES	☐ NO	Cleared to return to activity
☐ YES	☐ NO	Able to sprint at 8mph for 20 seconds
☐ YES	☐ NO	History of anterior cruciate ligament reconstruction within 5 years (for ACLR group)
☐ YES	☐ NO	No history of LE/low back surgery or injury (Healthy group)

Exclusion Criteria

☐ YES	☐ NO	Presence of knee/ patellofemoral joint effusion
☐ YES	☐ NO	Patellar tendonitis
☐ YES	☐ NO	Diagnosis of tibiofemoral osteoarthritis
☐ YES	☐ NO	Cruciate/ collateral knee ligament injuries or tears (other than anterior cruciate)
☐ YES	☐ NO	Previous surgery in the lower extremity within 12 months (other than ACL reconstruction)
☐ YES	☐ NO	Previous surgery in the low back within 12 months
☐ YES	☐ NO	Previous lower extremity/low back injury within 6 months
☐ YES	☐ NO	Known or suspected psychological disorder
☐ YES	☐ NO	Currently experiencing knee pain
☐ YES	☐ NO	Currently experiencing knee stiffness
☐ YES	☐ NO	Pregnant or breast feeding
☐ YES	☐ NO	Any form of inflammatory arthritis (e.g. RA, gout, pseudogout, lupus, etc)
☐ YES	☐ NO	Any other intra-articular knee joint injection during the study
☐ YES	☐ NO	Diagnosis of osteoarthritis

Session 1: Treadmill Exercise Testing for Cardiovascular Fitness

Stage	Time (min)	Velocity (mph)	HR	RPE	VO_2
Rest	0	0			
Baseline	0-2				
1	2-4				
2	4-6				
3	6-8				
4	8-10				
5	10-12				
6	12-14				
7	14-16				
8	16-18				
9	18-20				

Length of Exercise: _________

	HR	RPE	VO_2
Final Reading			

Session 2: Exercise Testing

Protocol: ☐Modified Balke
☐Data Driven

Stage	Time	HR	RPE	# Rounds	Reaction Time
Rest	0				
1	5				
Agility	5-6				
2	11				
Agility	11-12				
3	17				
Agility	17-18				
4	23				
Agility	23-24				
5	29				
Agility	29-30				

	HR	RPE
Final Reading		

Session 3: Exercise Testing

Protocol: ☐Modified Balke
☐Data Driven

Stage	Time	HR	RPE	# Rounds	Reaction Time
Rest	0				
1	5				
Agility	5-6				
2	11				
Agility	11-12				
3	17				
Agility	17-18				
4	23				
Agility	23-24				
5	29				
Agility	29-30				

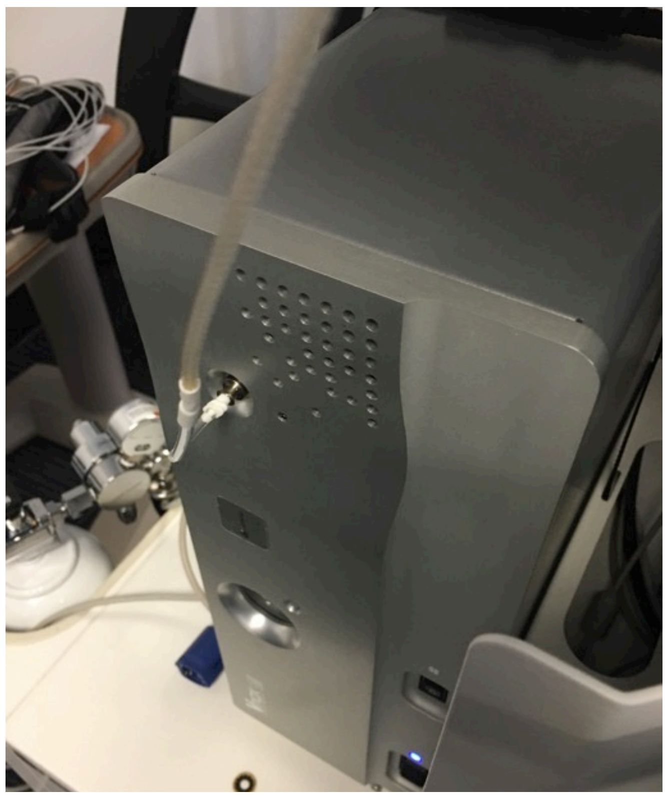
	HR	RPE
Final Reading		

Table C-11. Maximal Treadmill Testing

1. Open side of computer with penny (on right)
2. Turn on computer
3. Blue light means the metabolic cart is on
    a. Vmax – must be on at least 15 minutes before you can calibrate
4. Log on to the computer
5. Attach Flow Meter (from drying rack)
6. Three wires are attached to flow meter (Figure C-1)

7. Open Vmax on computer
8. Flow Sensor Calibration
9. Calibration:
    a. Pull table over for calibration – attach white tube of carefusion to flow meter (Figure C-2)

b. Flow sensor calibration
    i. F1: 2 strokes, space (hold hand over the end of flow meter is AC is on; If Flow > 0)
    ii. F1: strokes at different speeds (1st stroke doesn't pick up)
    iii. F3: stores the calibration
    iv. Replace the carefusion
c. White tube on flow meter to Vmax encore (Figure C-3)



d. Turn both gas tanks on in the back

10. If you get a warning:
    a. Make sure white cord was moved
    b. Gas tanks might be low

11. Calibrate O_2 and CO_2 (on the top menu):
    a. F1 (takes about 3 minutes)
    b. Flow meter calibration is good for about 2 hours – done when green
    c. Gas calibration is good for about 30 minutes
    d. F3 stores it
12. New study
    a. ID: __________
    b. Store as F3
13. Enter height, weight, DOB, ID, first name, last name
14. Store as F3
15. Turn gas tanks off
16. Move white cord back to flow meter
17. Attach HR monitor
18. Secure blue mask (Figure C-4)

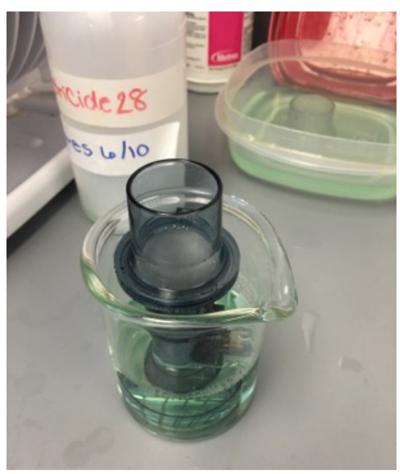
19. Plastic tube goes through blue mask
20. Once the mask is on, ask patient to put their hand over the open end – can you still breathe? If yes, mask is not tight enough.
21. Turn off gas after prompt to recalibrate (if you do multiple – leave on until done)
22. Exercise/Metabolic Test
    a. Start test
    b. F3 – put in mask (bypass calibration or recalibrate)

c. Start (F8)
d. Stage (Art likes 60s average for VO_2max)
e. Stage
    i. Ask patient: are you good to go the next stage?
f. Stage

23. Set the first run pace @ comfortable run pace for patient for 15-20 minutes.
24. Patient runs for 2 minutes.
25. Exit/Pause
26. Y? End test
27. Hit esc.
28. Tabular edit
    a. Average: 60s
    b. Edit Display: CPX Profile – Std
    c. F5: Output style w/ txt
    d. Hit Esc to exit out of system
29. Computer search for .txt file and move to desktop

<u>Cleaning process:</u>

30. Clean flow meter:
    a. Rinse flow meter, NEVER caged end up/ <u>ONLY horizontal</u>
    b. Sit for 5 minutes each side in metricide (Figure C-5)

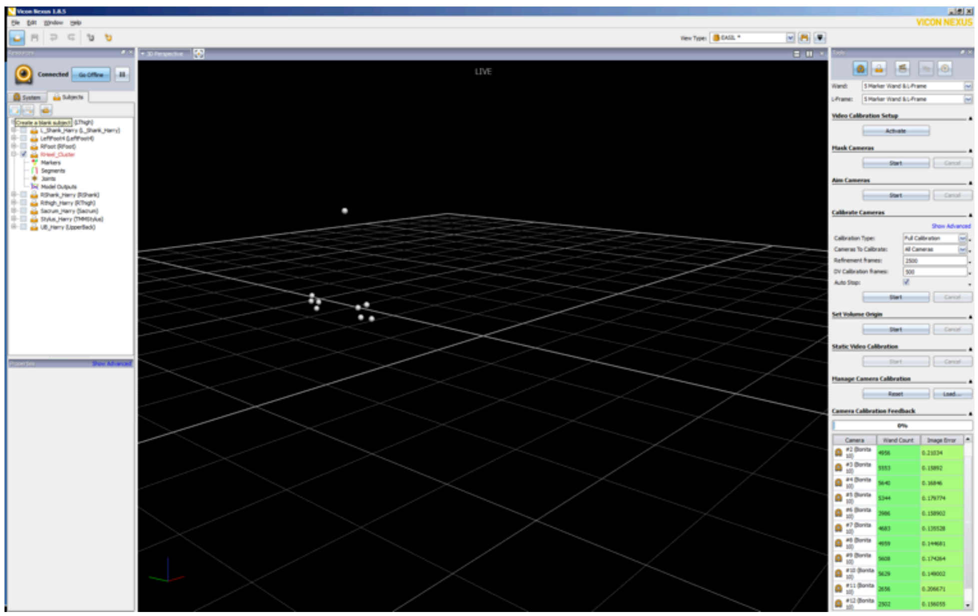


31. Soap bath for masks and head strap.
32. Little mouthpieces in metricide (Figure C-6)

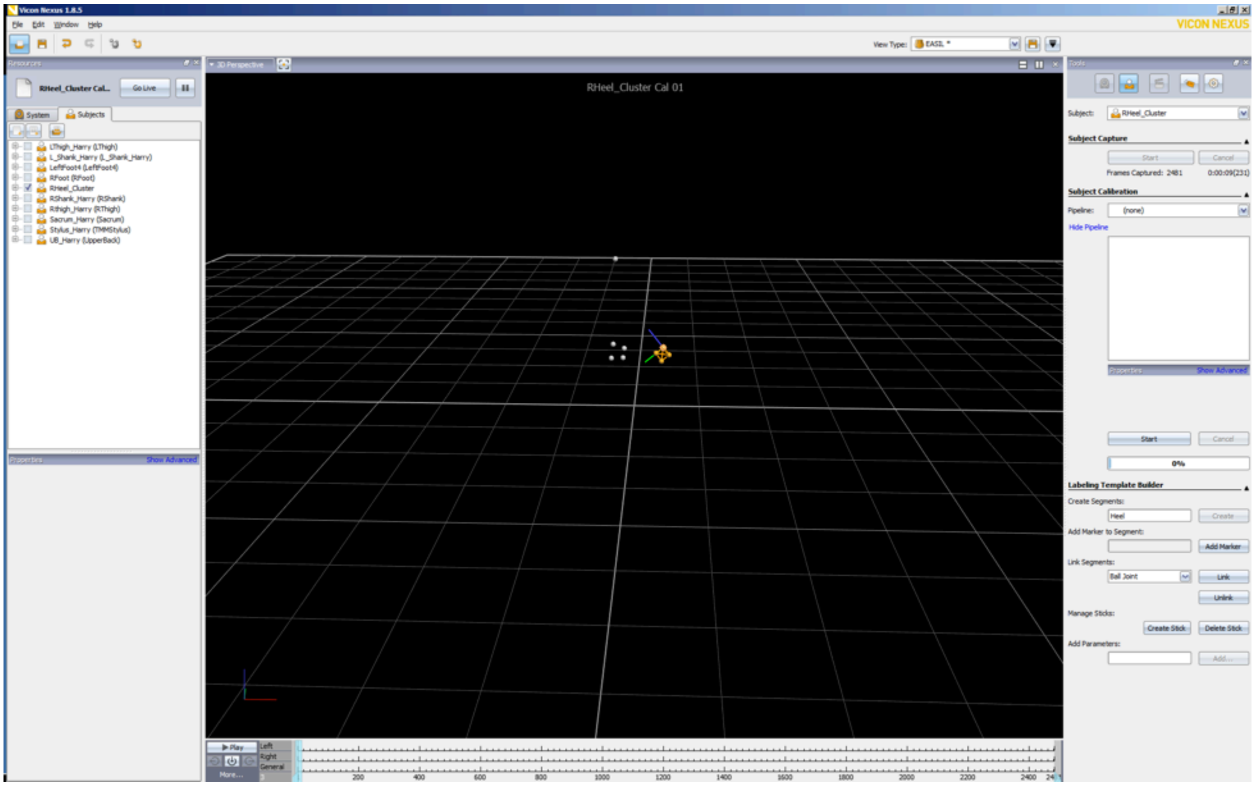
33. Fill plastic jar next to sink with de-ionized water
34. Spray mask with cavicide (sit for 5-10 minutes)
35. Pulse in and out of de-ionized water until it’s clean (flow meter sensor and small guys)

Table C-12. Creating Clusters

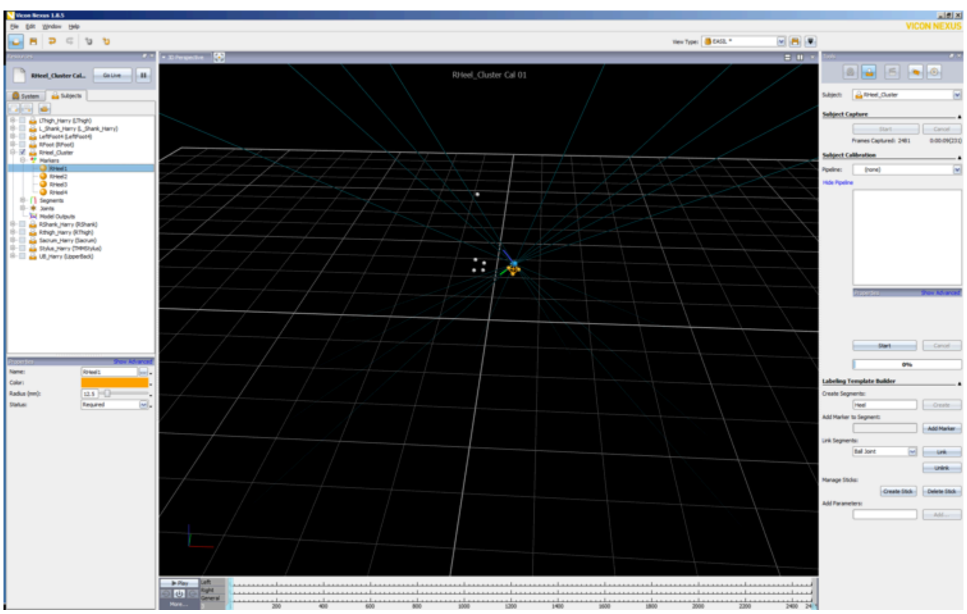
1. Turn on computer and open Vicon Nexus
    a. Make sure all cameras are green
    b. If any cameras are not green, unplug and reinsert corresponding camera cable
2. Change frame rate to 250Hz in Systems Tab
3. Have subject set up with cluster(s) enter capture space. Cover/remove extraneous reflective markers.
4. Click on Subjects Tab
5. Create a blank subject (Figure C-7)



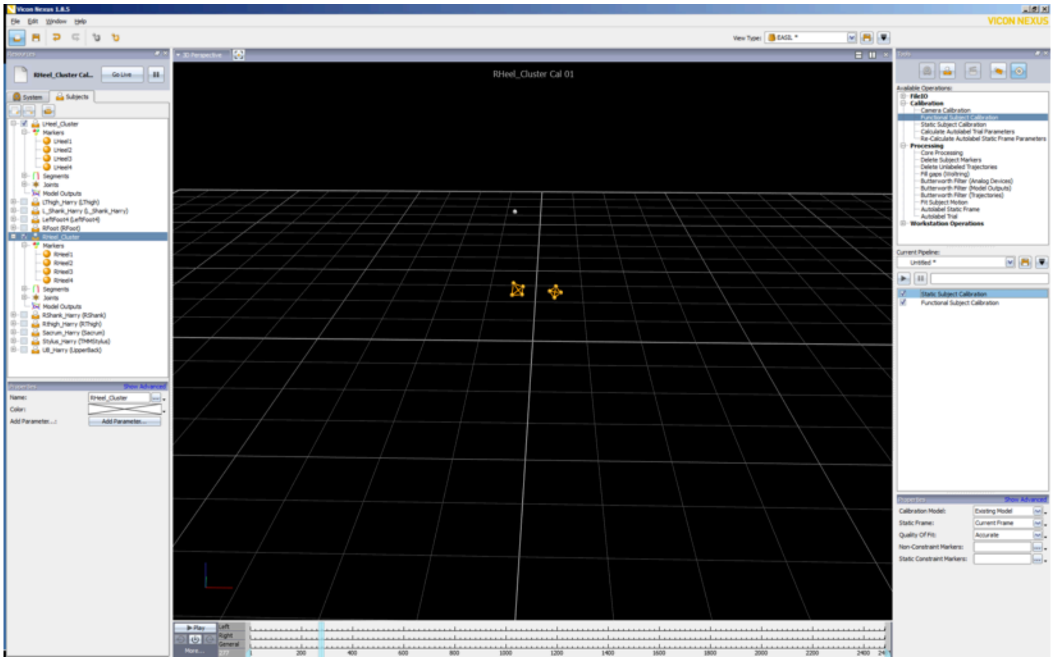
6. Label subject with cluster name
7. Go to Subject Tab under Tools Pane
    a. Make sure the current cluster is listed under Subject
8. Start subject capture
    a. Participant should stand still then complete dynamic movement based on task of interest (for gait, ask subject to march)
9. Stop subject capture after static and dynamic movement
10. Reconstruct pipeline using the grey balls on the top left menu bar
11. Create segment under the subject capture on the Tools pane
12. Name segment
13. Click on markers in the corresponding cluster (start top right and continue clockwise)
14. Click create (Figure C-8)



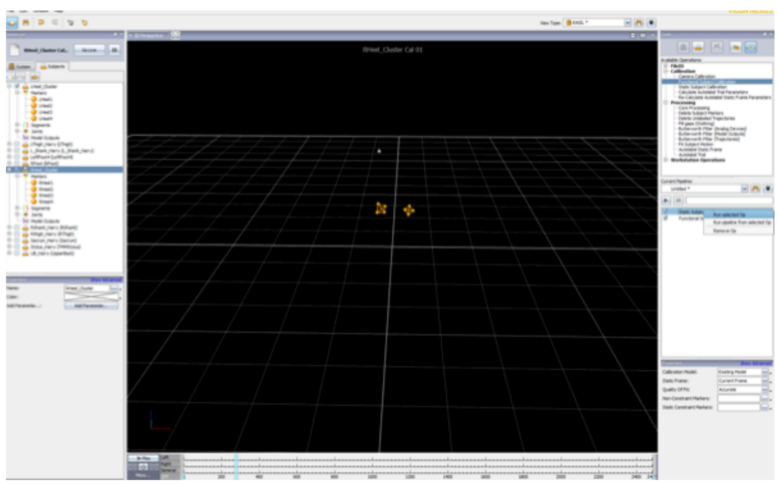
15. Click on Cluster in the Subjects Tab in the Resources Pane
    a. Expand Markers
    b. Label Markers in cluster (Figure C-9)



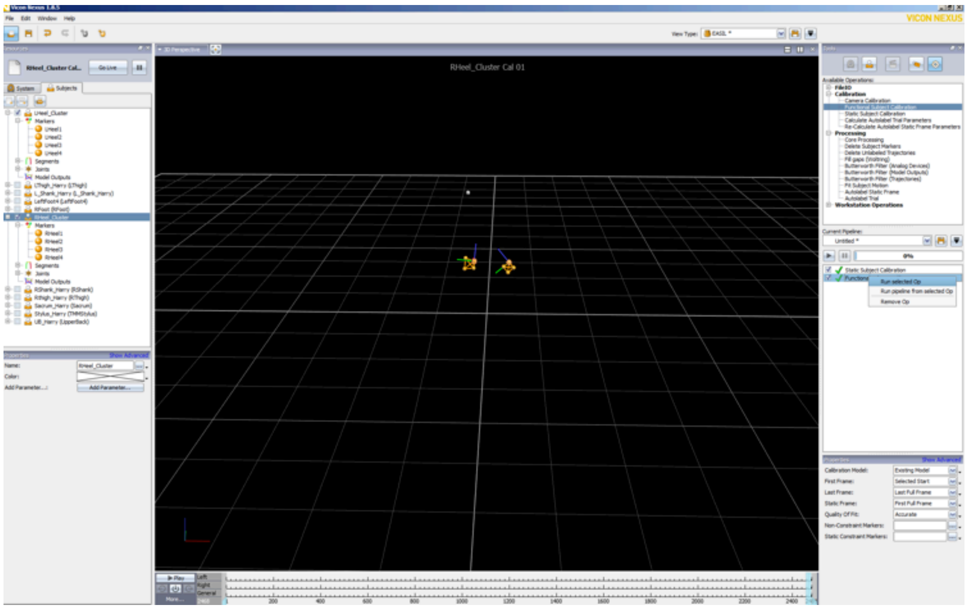
16. Go to the Pipeline Tab in the Tools Pane
17. Double click Static Subject Calibration and Functional Subject Calibration (Figure C-10)



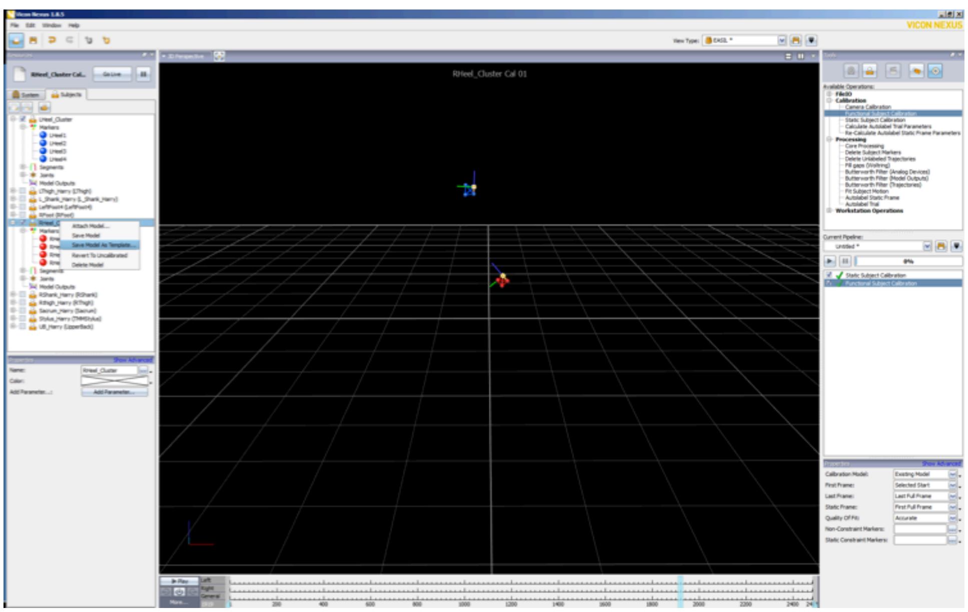
18. During a static frame, right click on Static Subject Calibration and Run Selected Op (Figure C-11)



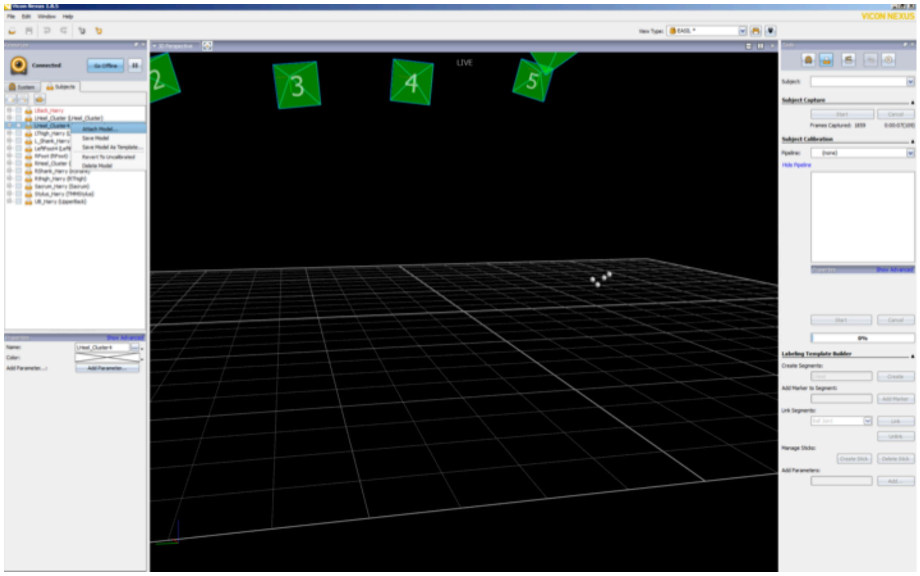
19. Play entire trial to make sure no markers are lost during dynamic task
    a. If marker is unlabeled, stop at that frame and relabel marker
20. Click on Functional Subject Calibration
    a. Start frame = First frame
    b. Last Frame = Last full Frame OR Current Frame
21. Right click on Functional Subject Calibration and Run Selected Op (Figure C-12)



22. Go to subjects tab on Resources Pane
23. Right click on the cluster
24. Save Model as Template (Figure C-13)



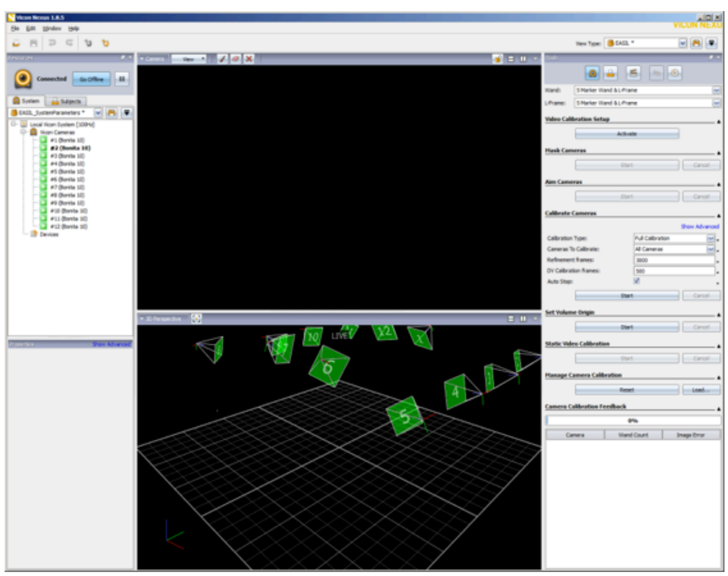
25. Right click on the cluster and choose Attach model. (Figure C-14)



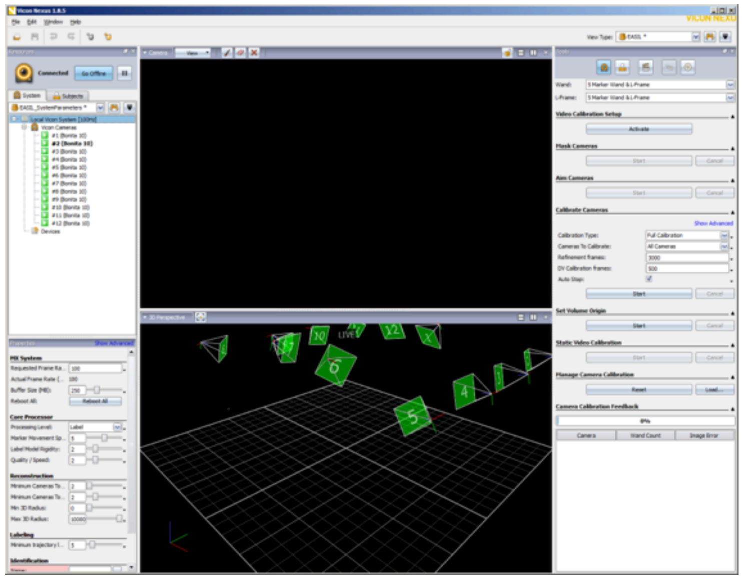
26. Attach the model created in #24.
27. Repeat steps 4-26 for each cluster.

Table C-13. Vicon and MotionMonitor Set-up Using the Cluster Markers

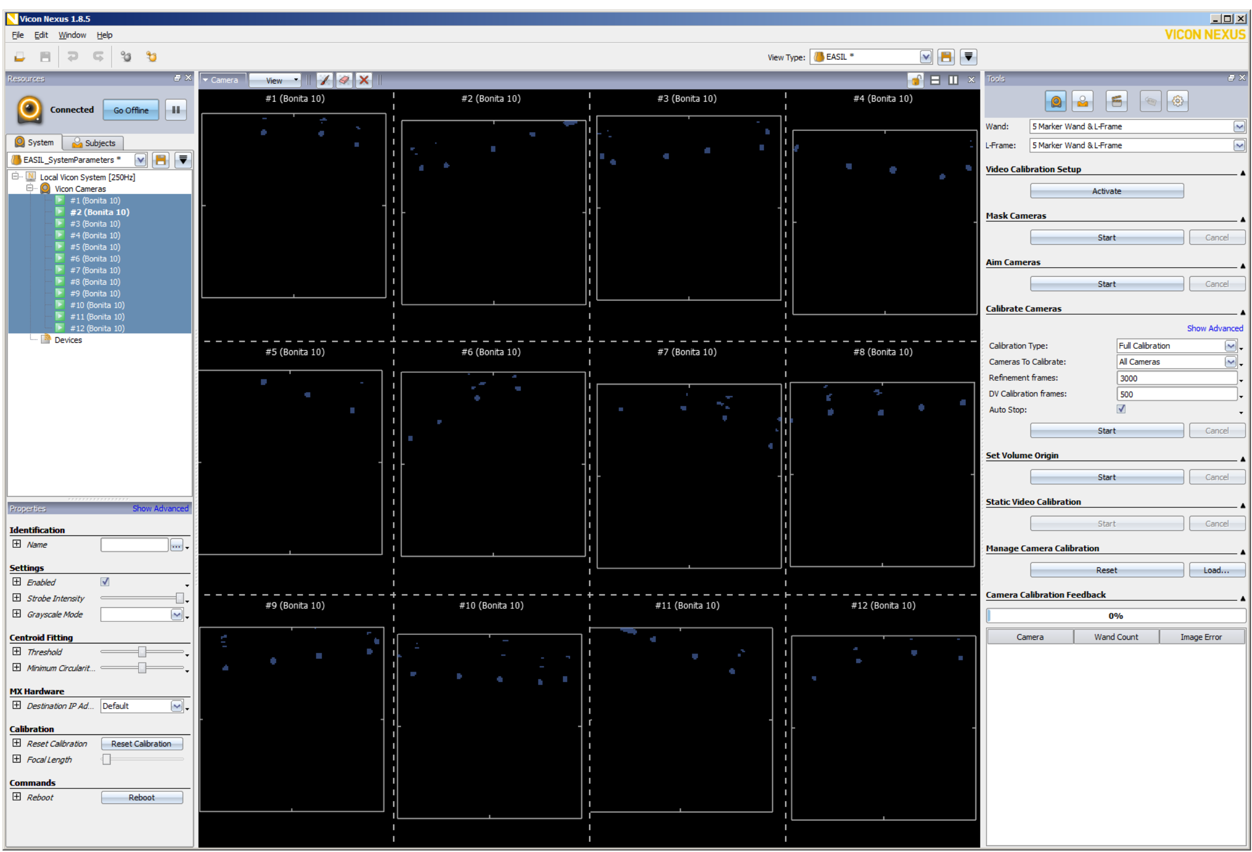
1. Turn on computer and open Vicon Nexus
    a. Make sure all cameras are green
    b. If any cameras are not green, unplug and reinsert corresponding camera cable (Figure C-15)



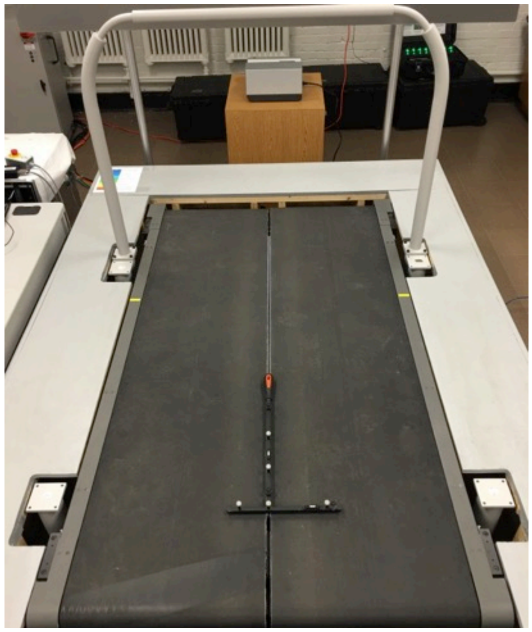
2. Change frame rate to 250 Hz (Figure C-16)



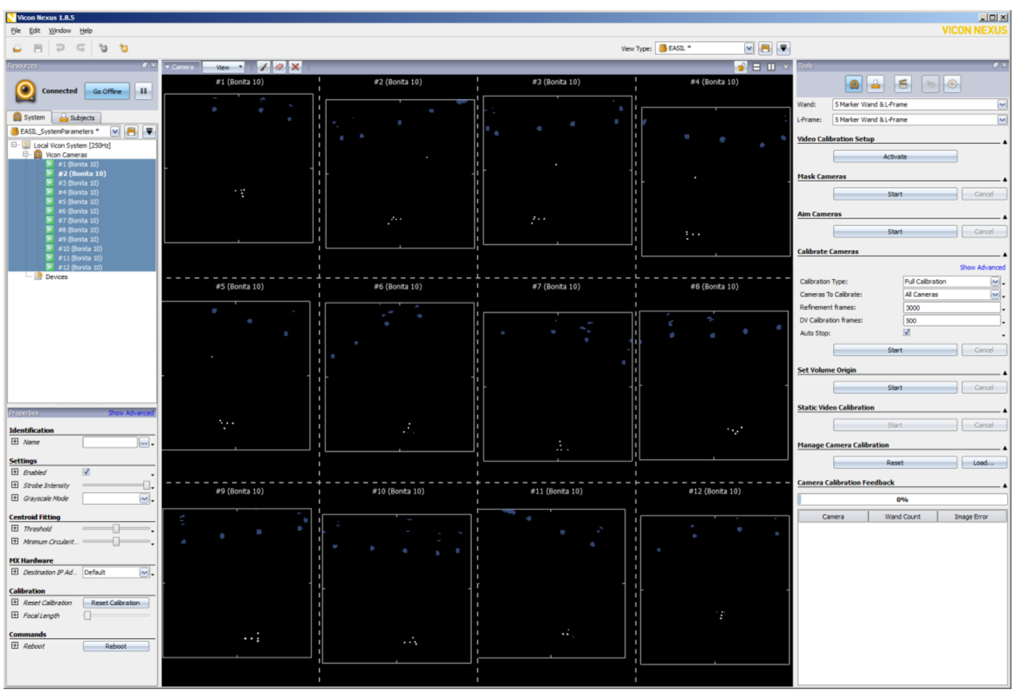
3. Select all cameras and change view to camera view
4. Remove all markers from the field
    a. If an unknown marker is in the field, try to locate it before masking cameras
5. Mask cameras
6. Select STOP once all reflectors in the field have changed to blue (Figure C-17)



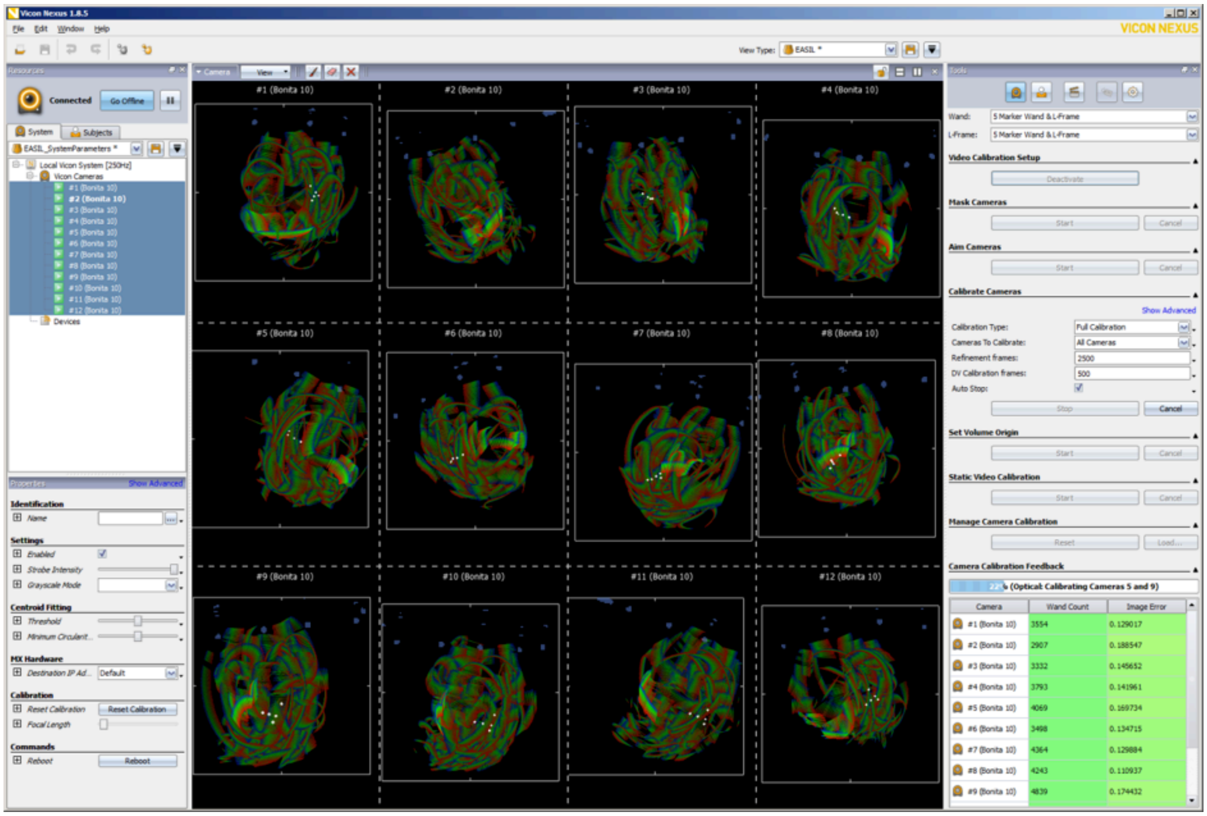
7. Place the L-wand in the field at the edge of the force plates (Figure C-18)



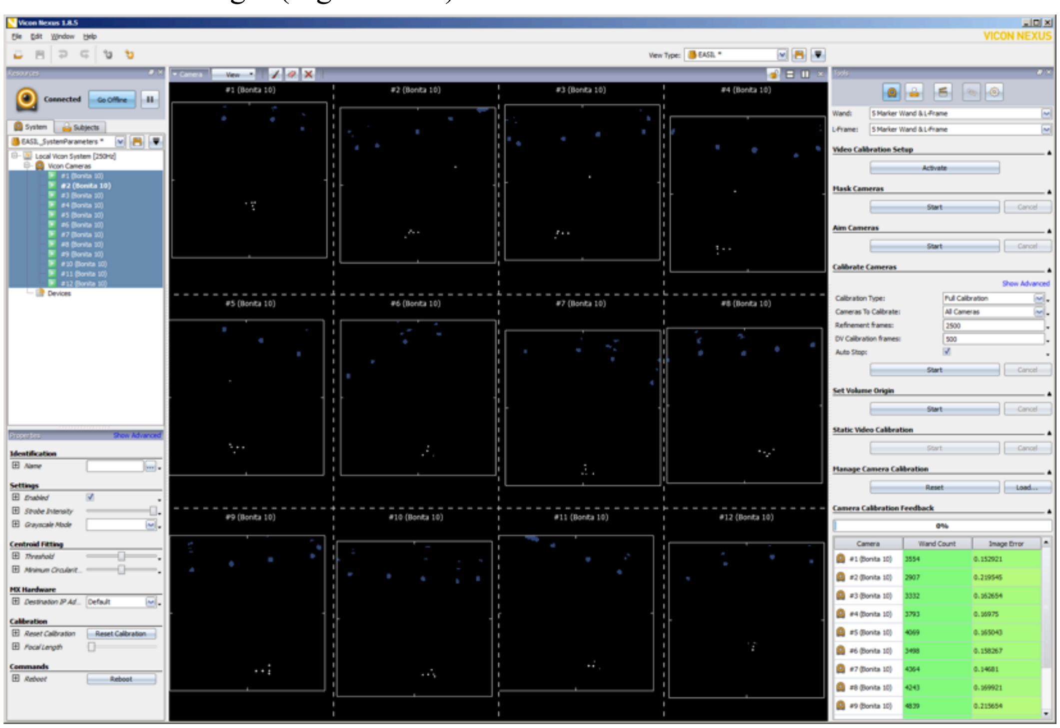
8. Aim Cameras (Figure C-19)



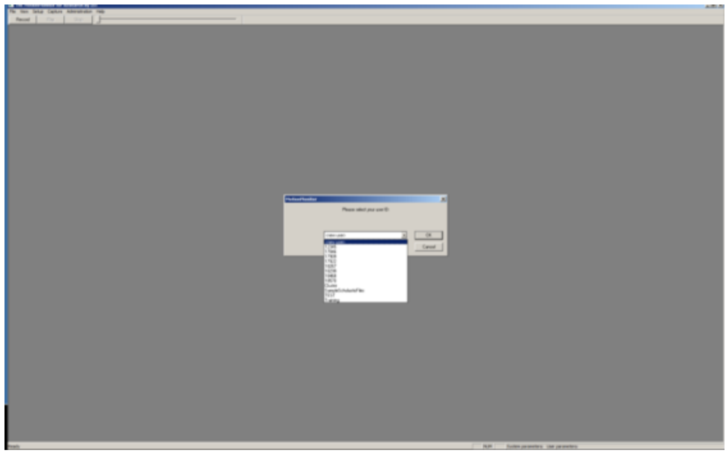
9. Calibrate cameras using 2500 refinement frames. Make sure to move the wand through all areas in the field where the subject will be moving (Figure C-20)



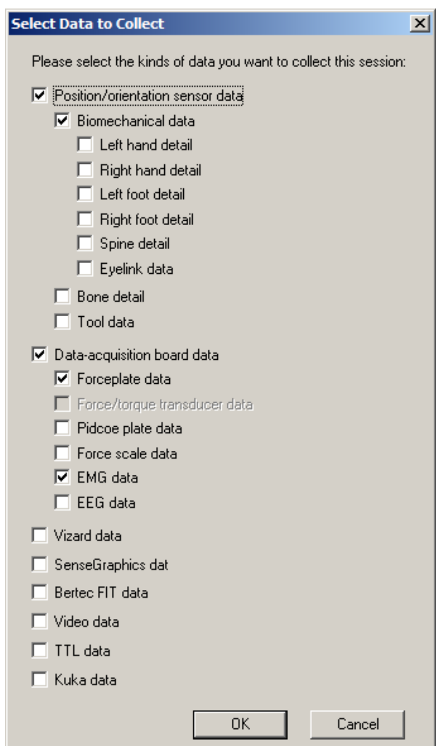
10. Check Image Error for any error greater than 0.25 – this may require recalibration
11. Replace the wand in the field (see picture in Step 7)
12. Set Volume Origin (Figure C-21)



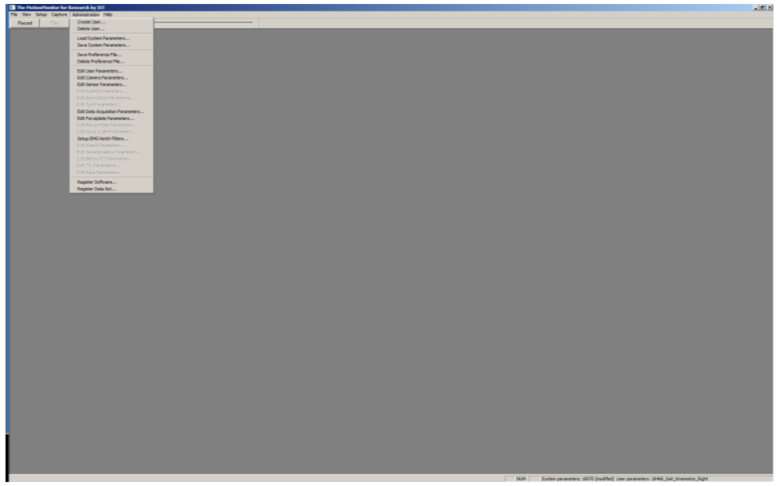
13. Select "Data Management" and select appropriate protocol for data collection
14. Select "Subjects' tab to verify cluster files have loaded.
    a. Press Control-R and markers on participant will be recognized to create model.
15. Open MotionMonitor with corresponding username (IRB #) (Figure C-22)



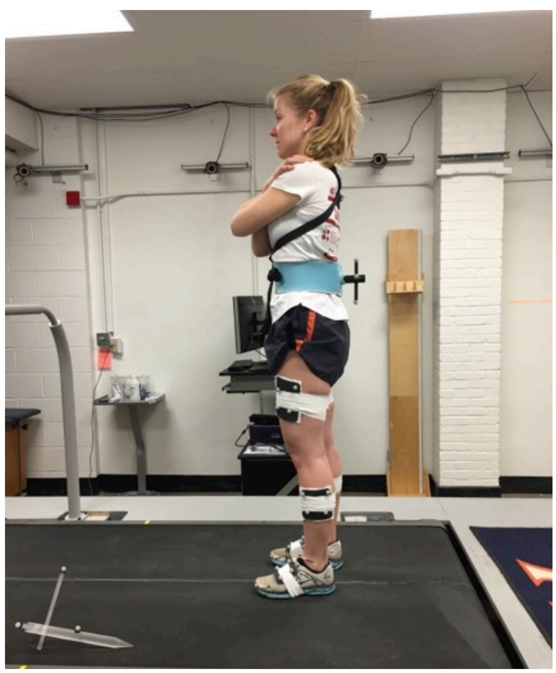
16. Select data to collect: Make sure Position/orientation sensor data, Biomechanical data, Data-acquisition data, forceplate data, and EMG data are checked (Figure C-23)



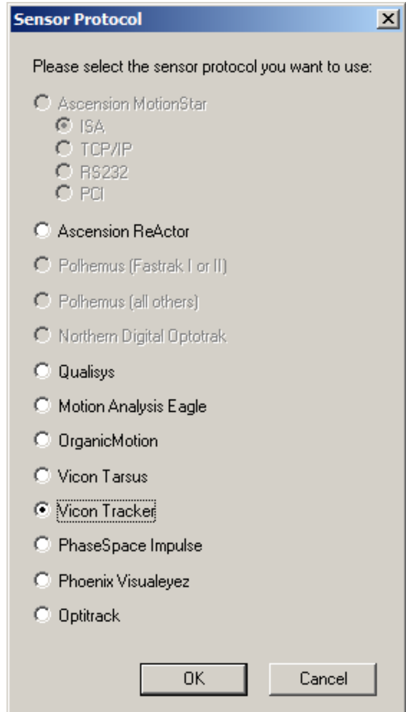
17. Go to the top menu and select Administration and Load System Parameters. Load corresponding system parameters (IRB #) (Figure C-24)



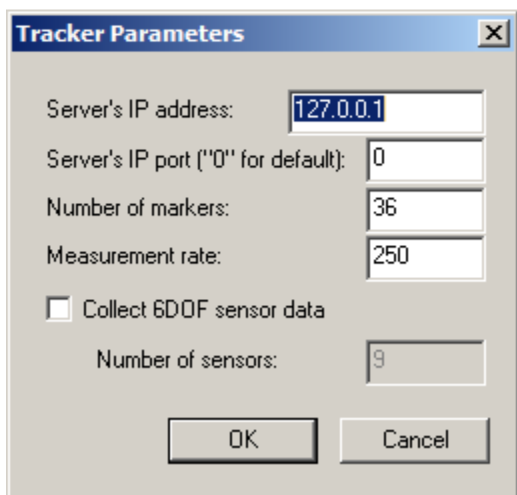
18. Go to the top menu and select File and Preference File. Load appropriate preference file.
19. Subject should enter the field (stand on the treadmill) with all clusters attached and the stylus need to be placed within the field (Figure C-25)



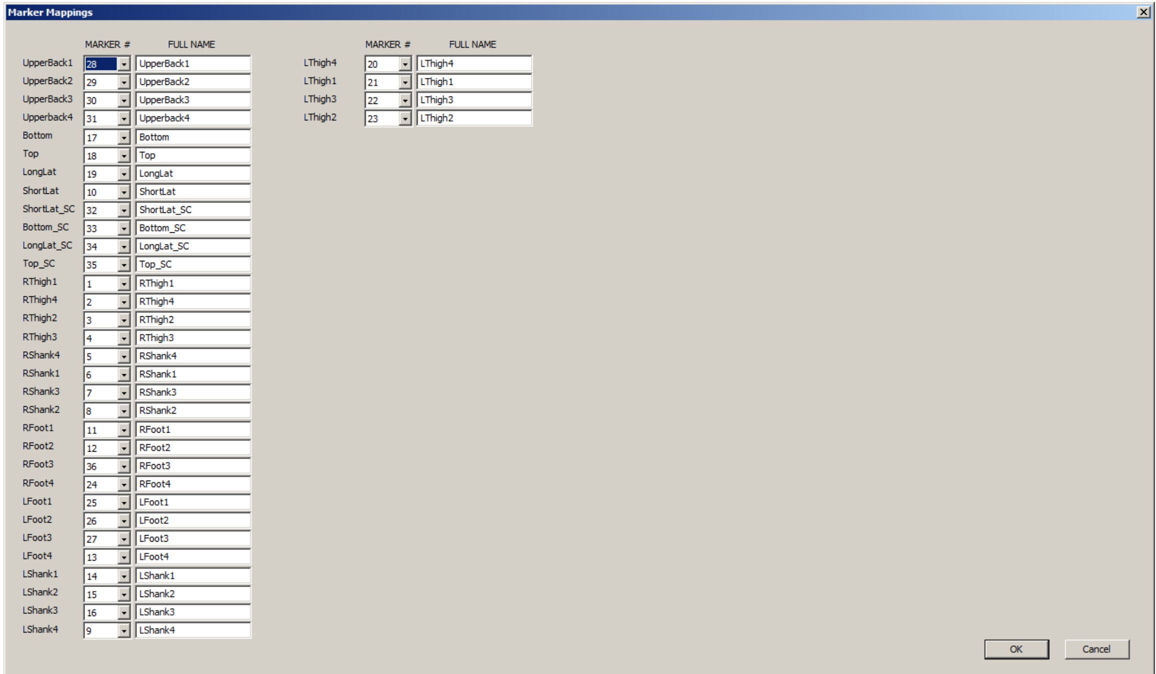
20. Go to the top menu and select Administration then select Edit Sensor Parameters.
21. Select Vicon Tracker (Figure C-26)

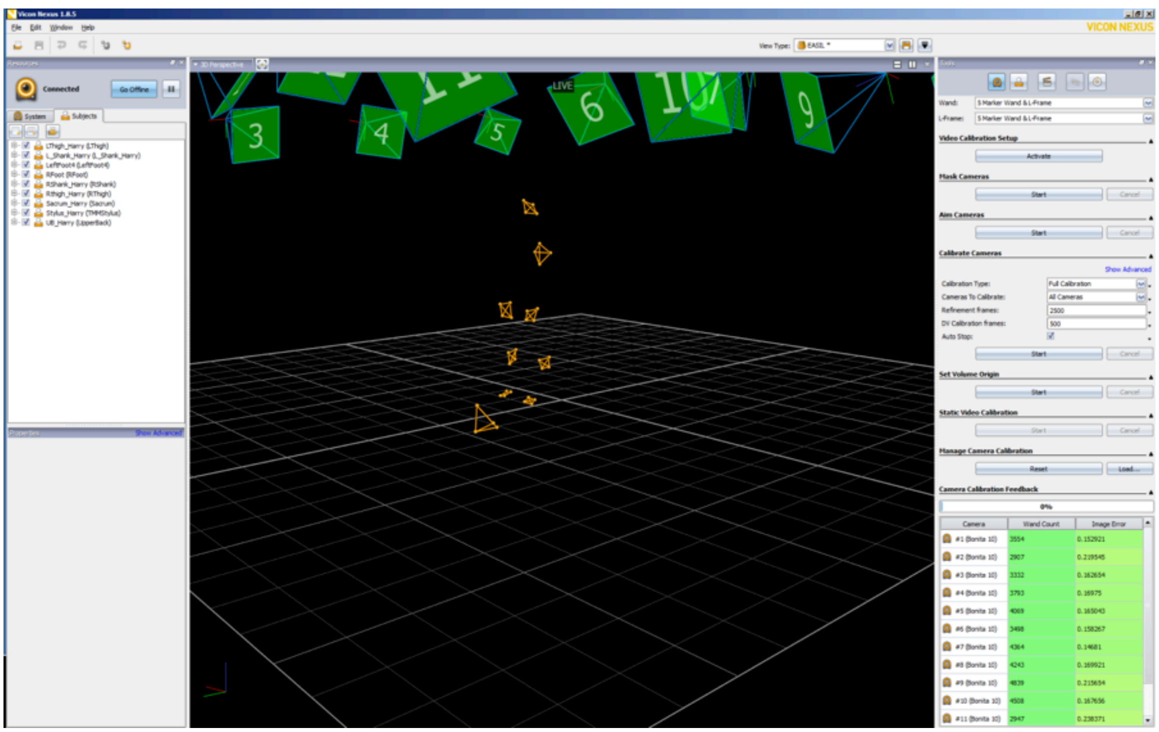


22. Confirm that number of markers = 36 and measurement rate = 250Hz (Figure C-27)

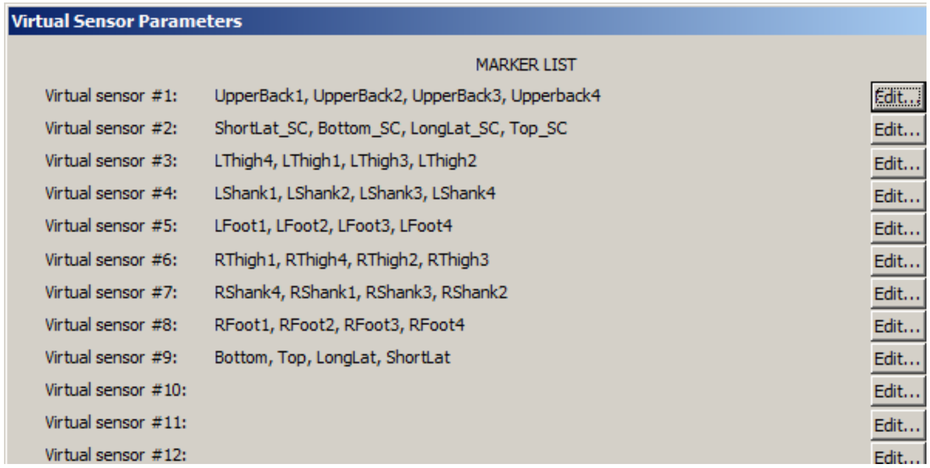


23. Confirm that all 36 markers are recognized (Figure C-28, Figure C-29)

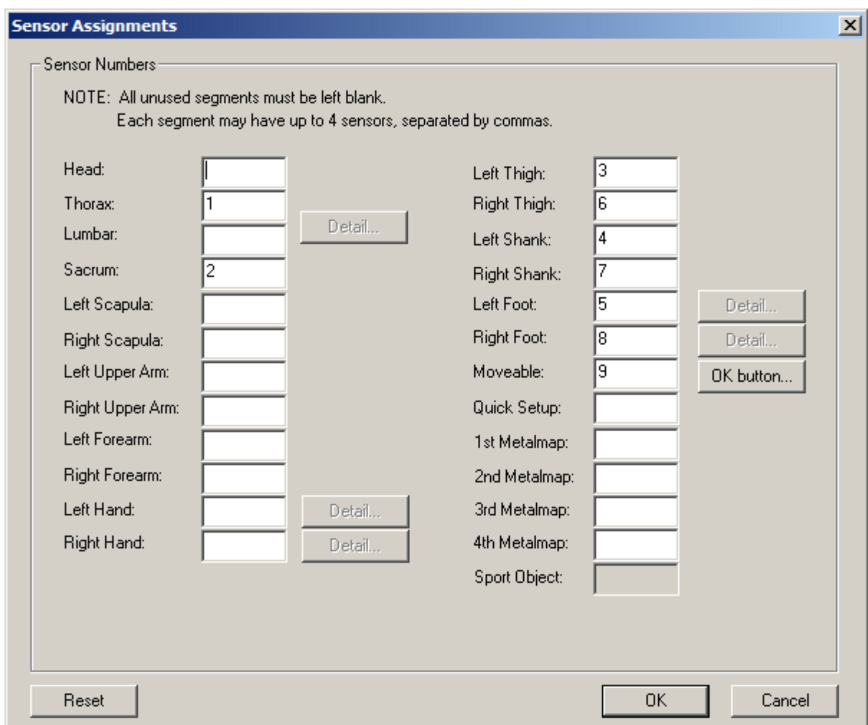




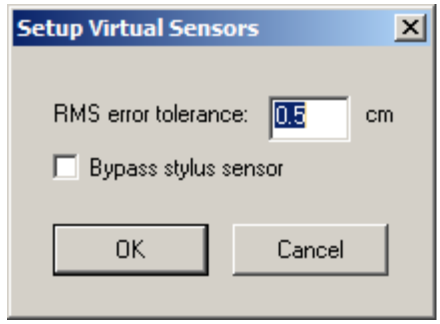
24. Confirm all clusters are assigned to appropriate virtual sensor (Figure C-30)



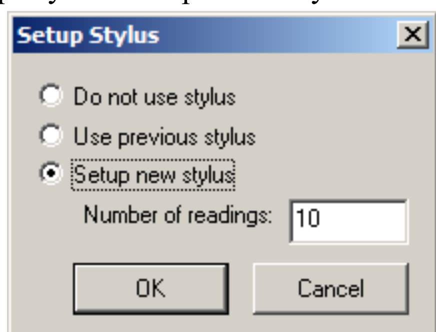
25. Go to the top menu and select setup and Edit Sensor Assignments. Sensor assignments listed should match assignments in virtual sensor parameters (see previous step) (Figure C-31)



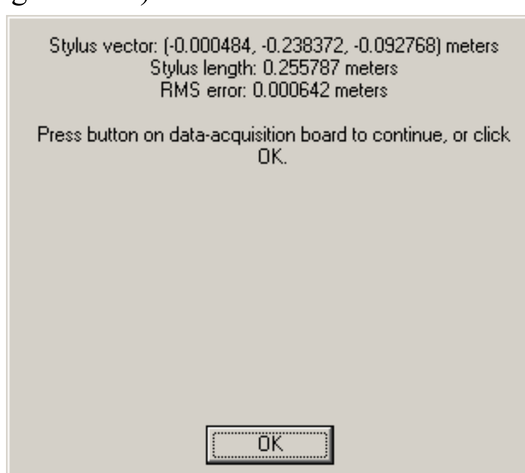
26. Ask the subject to stand still with hands crossed on the shoulders
27. Go to Vicon Nexus window and press Control-R
28. Return to MotionMonitor window and go to the top menu and select Setup and Setup Virtual Sensors (Figure C-32)



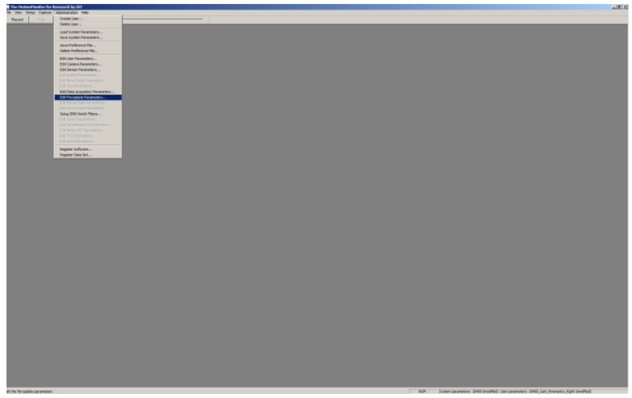
29. If you DO NOT receive an error, continue to step 30. If you DO receive an error, go back to step 20.
30. Ask Subject to step onto the mat behind the treadmill.
31. Select Setup and Select Data to Collect. Uncheck EMG data.
32. Select Setup and Setup Stylus. Setup a new stylus with 10 readings (Figure C-33)



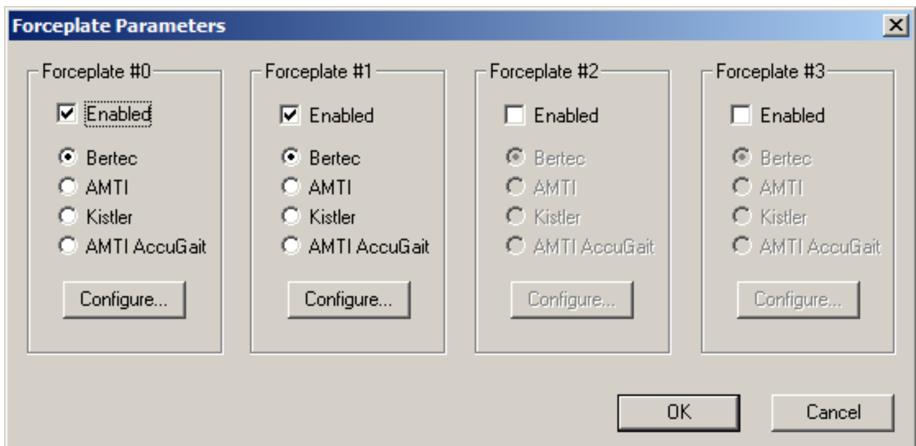
33. Calibrate stylus (Figure C-34)



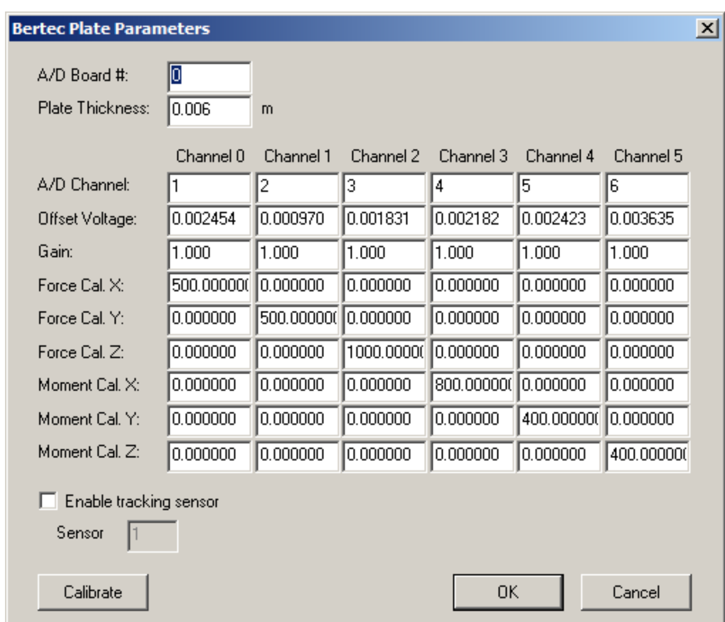
34. Remove all weight from forceplates. Zero the forceplates in the hardware.
35. Go to Administration and Edit Forceplate Parameters (Figure C-35)



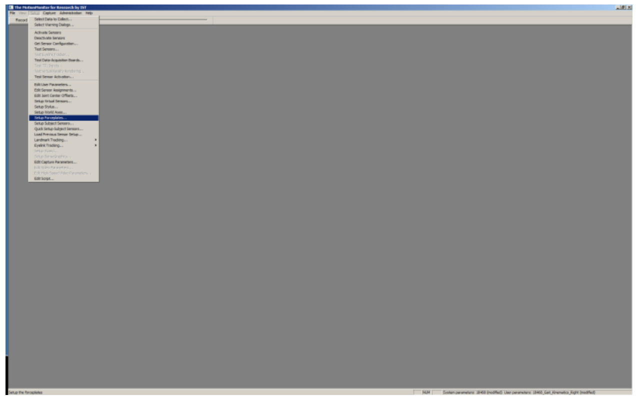
36. Select Configure for Forceplate #0 (Figure C-36)

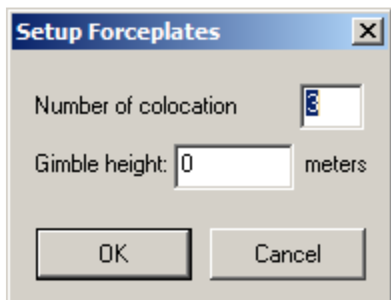


37. Select Calibrate (Figure C-37)

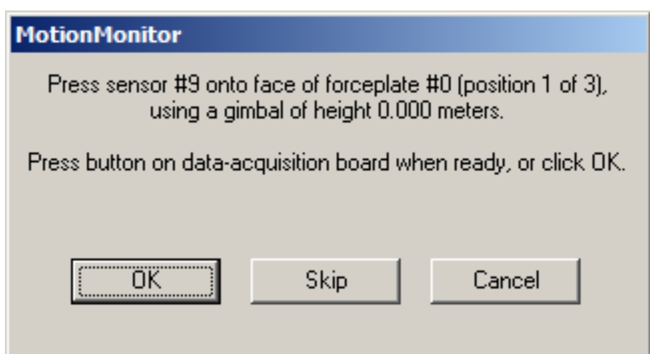


38. Select OK and repeat steps for Forceplate #1
39. Go to the top menu and select Setup and Setup Forceplates (Figure C-38, Figure C-39)



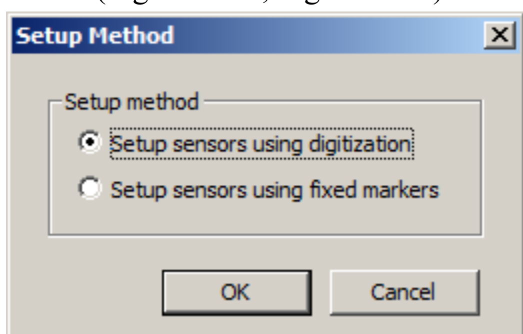


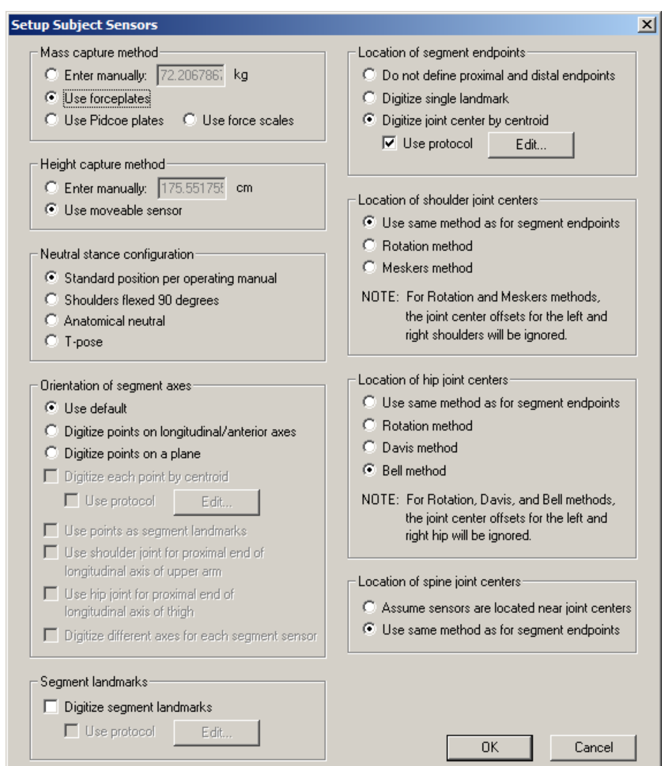
40. Using the stylus, press into the forceplate at three non-linear locations (Figure C-40)



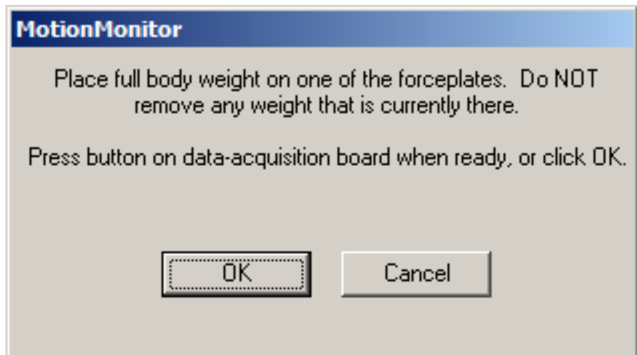
41. Error should be less than 1 cm. If it is greater than 1.0, repeat steps 34-40 (Figure C-41)

42. Go to the top menu and select Setup and Setup Subject Sensors. Select setup sensors using digitization (Figure C-42, Figure C-43)

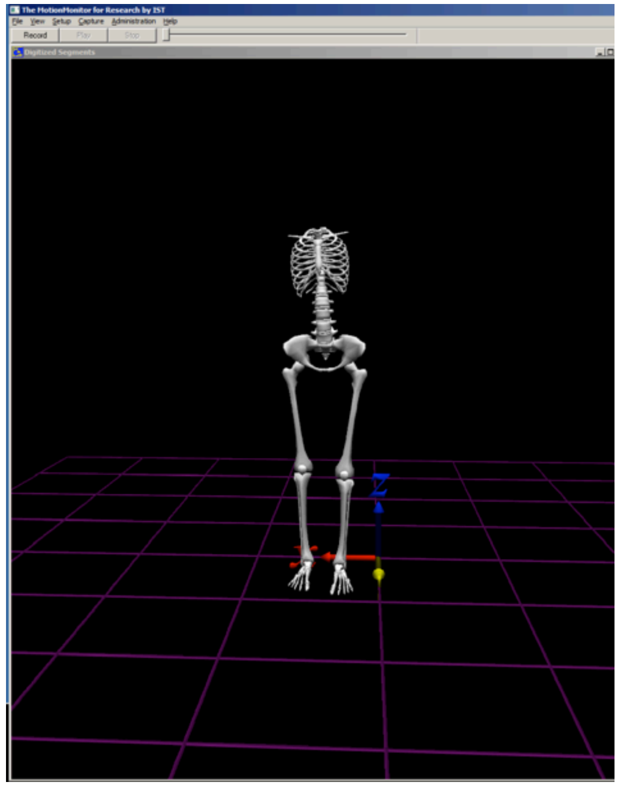


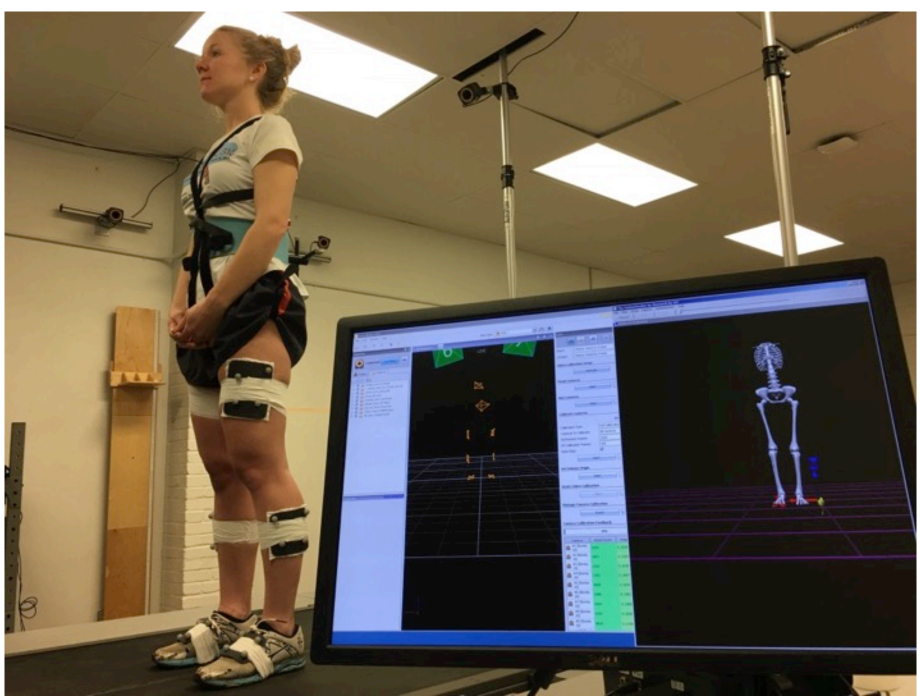


43. With below image on screen, ask subject to step onto ONE of the forceplates (one treadmill belt) with both feet. Once subject is in place, click “OK” to record body weight (Figure C-44)



44. Place the tip of the stylus on top of the subject’s head when prompted by MotionMonitor. Make sure height and weight are accurate (around what you would expect). Hold still with stylus to don sensors.
45. Point out the following landmarks on the subject in the following order (hitting Control-R on Vicon Nexus screen as appropriate):
    a. Left ASIS
    b. Right ASIS (hold still to get final hip reading)
    c. C7/T1
    d. T12/L1
    e. L5/S1
    f. Left Lateral Knee Joint Line
    g. Left Medial Knee Joint Line
    h. Left Lateral Malleolus
    i. Left Medial Malleolus
    j. Left Tip of 2^{nd} Phalanx
    k. Right Lateral Knee Joint Line
    l. Right Medial Knee Joint Line
    m. Right Lateral Malleolus
    n. Right Medial Malleolus
    o. Right Tip of 2^{nd} Phalanx
46. If skeleton looks appropriate, continue with collection. If anything does not look right, redigitize the skeleton (redo steps 42-45) (Figure C-45, Figure C-46).

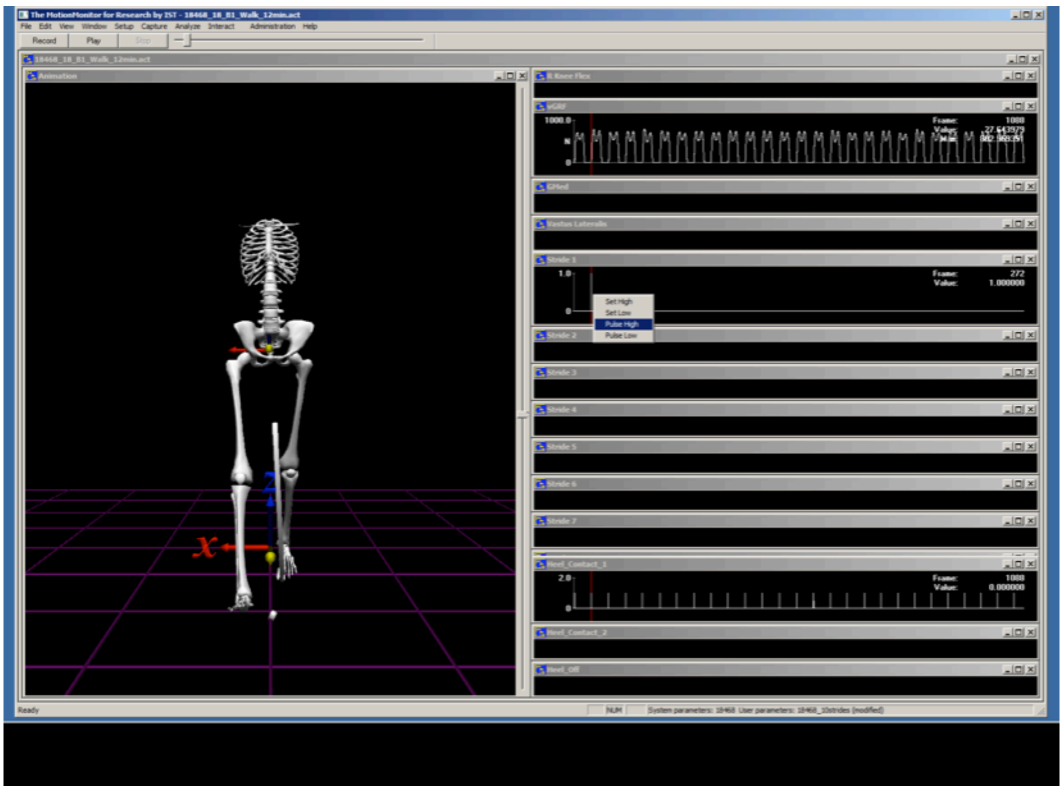




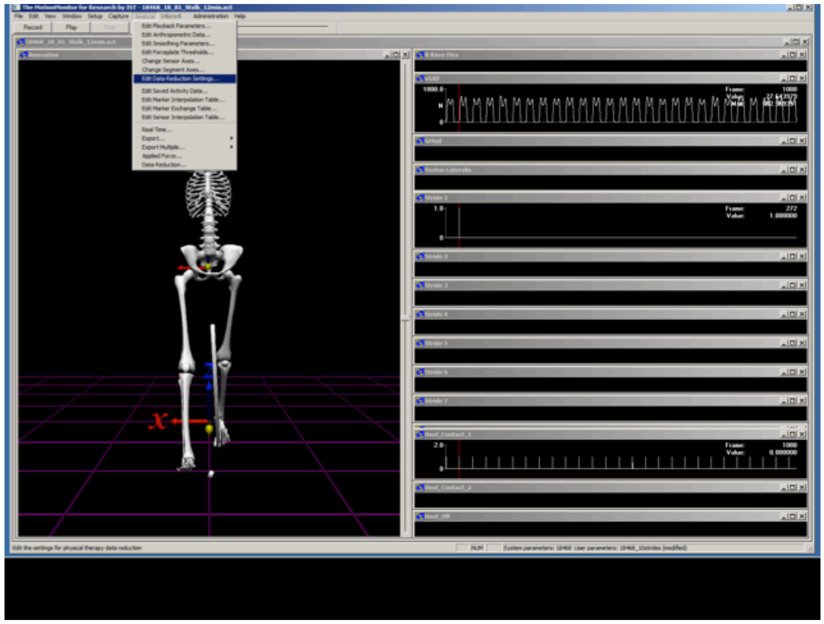
47. Go to the top menu and select Setup and Select Data to Collect.

Table C-14. Data Processing for Gait Strides

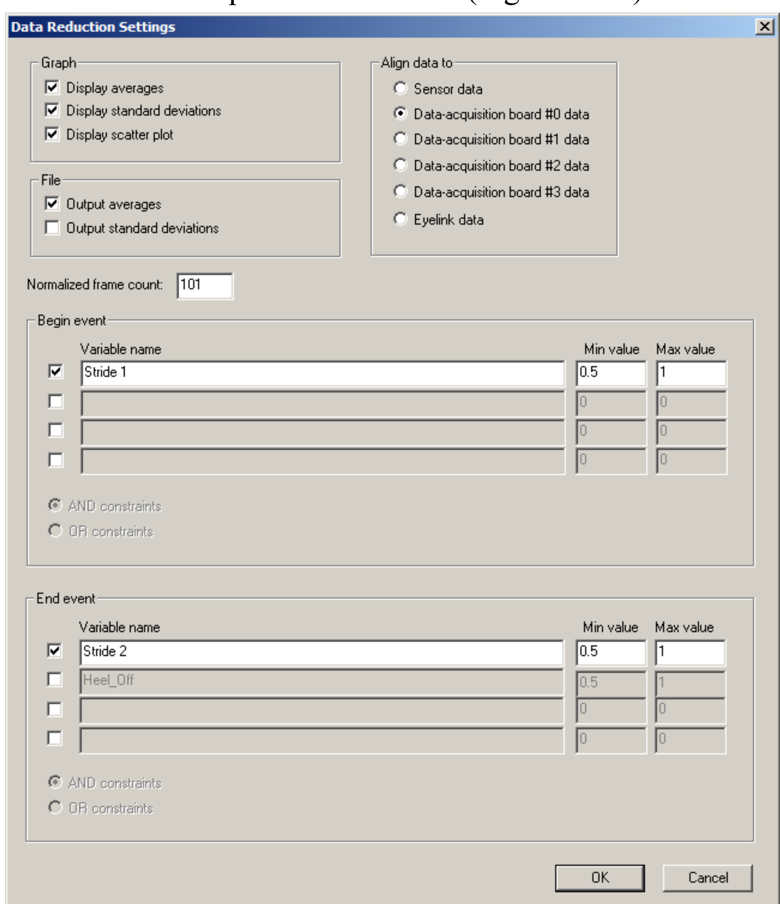
1. Open MotionMonitor
2. Go to File → Open Trial
3. Set Heel Strike when raw vertical ground reaction force > 20N
    a. Expand stride window
    b. Make sure cursor is at the point when vGRF > 20N
    c. Right click on stride window
    d. Set pulse high (Figure C-47)



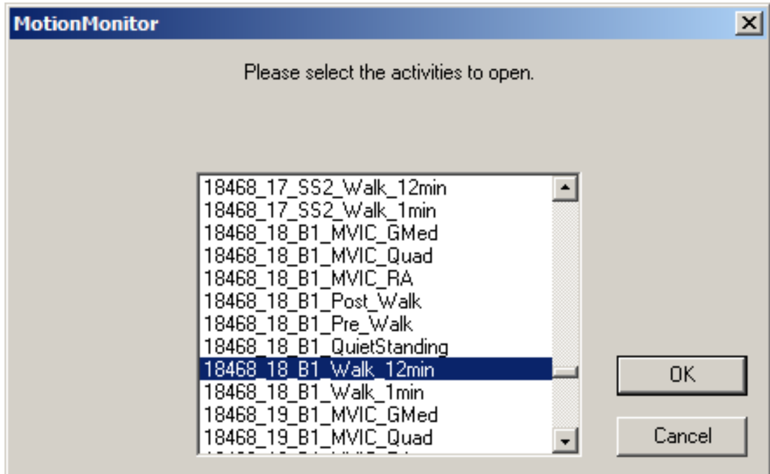
4. Set ipsilateral heel strike for consecutive strides
5. Go to Analyze → Edit Data Reduction Settings (Figure C-48)



6. Under Data Reduction Settings set the variable names from the beginning to the end of gait cycle (heel strike to ipsilateral heel strike)
    a. Align data to Data-Acquisition Board #0 (Figure C-49)



7. Click OK
8. Go to Analyze → Data Reduction
9. Select User Activity
10. Select Trial(s) to export (Figure C-50)
    a. If multiple trials are selected, the output will be the average. Make sure standard deviation is checked under data reduction settings in these cases



11. Click OK
12. Save file as an excel file

Table C-15. Graded Treadmill Exercise (Walking Exercise)

1. Complete subject preparation with reflective markers
2. After system and subject calibration, record quiet standing data on treadmill
3. Record heart rate and Borg scale rating (RPE)
4. Subject should walk for 2 minutes at 1.34 m/s and run for 2 minutes at 3.33m/s at 0.0° incline.
5. Collect walking
6. Collect running
7. Begin Exercise Protocol
    a. Interval I
        i. Subject walks for the first minute at 0.0° incline
        ii. Subject walks for the second minute at 0.5° incline
        iii. Subject walks for the third minute at 1.0° incline
        iv. Subject walks for the fourth minute at 1.5° incline
        v. Subject walks for the fifth minute at 2.0° incline
        vi. Record heart rate and RPE rating in the last 15 seconds of minute five

vii. Treadmill stops and subject steps off treadmill
viii. Subjects completes 1 minute of alternating floor exercises
1. 10 repetitions of squat jumps
2. 10 repetitions of lateral hopping

b. Interval II
i. Subject walks for the first minute at 2.0° incline
ii. Subject walks for the second minute at 2.5° incline
iii. Subject walks for the third minute at 3.0° incline
iv. Subject walks for the fourth minute at 3.5° incline
v. Subject walks for the fifth minute at 4.0° incline
vi. Record heart rate and RPE rating in the last 15 seconds of minute five
vii. Treadmill stops and subject steps off treadmill
viii. Subject completes 1 minute of alternating floor exercises
1. 10 repetitions of squat jumps
2. 10 repetitions of lateral hopping

c. Interval III
i. Subject walks for the first minute at 4.0° incline
ii. Subject walks for the second minute at 4.5° incline
iii. Subject walks for the third minute at 5.0° incline
iv. Subject walks for the fourth minute at 5.5° incline
v. Subject walks for the fifth minute at 6.0° incline
vi. Record heart rate and RPE rating in the last 15 seconds of minute five
vii. Treadmill stops and subject steps off treadmill
viii. Subject completes 1 minute of alternating floor exercises
1. 10 repetitions of squat jumps
2. 10 repetitions of lateral hopping

d. Interval IV
i. Subject walks for the first minute at 6.0° incline
ii. Subject walks for the second minute at 6.5° incline
iii. Subject walks for the third minute at 7.0° incline
iv. Subject walks for the fourth minute at 7.5° incline
v. Subject walks for the fifth minute at 8.0° incline
vi. Record heart rate and RPE rating in the last 15 seconds of minute five

vii. Treadmill stops and subject steps off treadmill
viii. Subject completes 1 minute of alternating floor exercises
1. 10 repetitions of squat jumps
2. 10 repetitions of lateral hopping

e. Interval V
i. Subject walks for the first minute at 8.0° incline
ii. Subject walks for the second through fifth minutes at 8.5° incline
iii. Record heart rate and RPE rating in the last 15 seconds of minute five
iv. Treadmill stops and subject steps off treadmill
v. Lower treadmill to 0.0° incline
vi. Subject completes 1 minute of alternating floor exercises
1. 10 repetitions of squat jumps
2. 10 repetitions of lateral hopping
vii. Record heart rate and RPE rating immediately after floor exercises
viii. Subject returns to treadmill
ix. Collect walking
x. Collect running

Table C-16. Data-Driven Exercise (Interval Exercise)

1. Complete subject preparation with reflective markers
2. After system and subject calibration, record quiet standing data on treadmill
3. Record heart rate and Borg scale rating (RPE)
4. Subject should walk for 2 minutes at 1.34 m/s and run for 2 minutes at 3.33m/s at 0.0° incline.
5. Collect walking
6. Collect running
7. Begin Exercise Protocol
   a. Interval I
      i. Subject walks at 1.34m/s for 15 seconds
      ii. Subject jogs at 2.68m/s for 25 seconds
      iii. Subject runs at 3.33m/s for 20 seconds
      iv. Subject walks at 1.34m/s for 15 seconds
      v. Subject jogs at 2.68m/s for 25 seconds
      vi. Subject runs at 3.33m/s for 20 seconds
      vii. Subject walks at 1.34m/s for 15 seconds

viii. Subject jogs at 2.68m/s for 25 seconds
ix. Subject runs at 3.33m/s for 20 seconds
x. Subject walks at 1.34m/s for 15 seconds
xi. Subject jogs at 2.68m/s for 25 seconds
xii. Subject runs at 3.33m/s for 20 seconds
xiii. Subject walks at 1.34m/s for 15 seconds
xiv. Subject jogs at 2.68m/s for 25 seconds
xv. Subject runs at 3.33m/s for 20 seconds
xvi. Stop treadmill and record heart rate and RPE rating
xvii. Subject steps off treadmill
xviii. Subjects completes 1 minute of agility with reactive lights

b. Interval II
    i. Subject walks at 1.34m/s for 15 seconds
    ii. Subject jogs at 2.68m/s for 25 seconds
    iii. Subject runs at 3.33m/s for 20 seconds
    iv. Subject walks at 1.34m/s for 15 seconds
    v. Subject jogs at 2.68m/s for 25 seconds
    vi. Subject runs at 3.33m/s for 20 seconds
    vii. Subject walks at 1.34m/s for 15 seconds
    viii. Subject jogs at 2.68m/s for 25 seconds
    ix. Subject runs at 3.33m/s for 20 seconds
    x. Subject walks at 1.34m/s for 15 seconds
    xi. Subject jogs at 2.68m/s for 25 seconds
    xii. Subject runs at 3.33m/s for 20 seconds
    xiii. Subject walks at 1.34m/s for 15 seconds
    xiv. Subject jogs at 2.68m/s for 25 seconds
    xv. Subject runs at 3.33m/s for 20 seconds
    xvi. Stop treadmill and record heart rate and RPE rating
    xvii. Subject steps off treadmill
    xviii. Subjects completes 1 minute of agility with reactive lights

c. Interval III
    i. Subject walks at 1.34m/s for 15 seconds
    ii. Subject jogs at 2.68m/s for 25 seconds
    iii. Subject runs at 3.33m/s for 20 seconds
    iv. Subject walks at 1.34m/s for 15 seconds
    v. Subject jogs at 2.68m/s for 25 seconds

vi. Subject runs at 3.33m/s for 20 seconds
vii. Subject walks at 1.34m/s for 15 seconds
viii. Subject jogs at 2.68m/s for 25 seconds
ix. Subject runs at 3.33m/s for 20 seconds
x. Subject walks at 1.34m/s for 15 seconds
xi. Subject jogs at 2.68m/s for 25 seconds
xii. Subject runs at 3.33m/s for 20 seconds
xiii. Subject walks at 1.34m/s for 15 seconds
xiv. Subject jogs at 2.68m/s for 25 seconds
xv. Subject runs at 3.33m/s for 20 seconds
xvi. Stop treadmill and record heart rate and RPE rating
xvii. Subject steps off treadmill
xviii. Subjects completes 1 minute of agility with reactive lights

d. Interval IV
    i. Subject walks at 1.34m/s for 15 seconds
    ii. Subject jogs at 2.68m/s for 25 seconds
    iii. Subject runs at 3.33m/s for 20 seconds
    iv. Subject walks at 1.34m/s for 15 seconds
    v. Subject jogs at 2.68m/s for 25 seconds
    vi. Subject runs at 3.33m/s for 20 seconds
    vii. Subject walks at 1.34m/s for 15 seconds
    viii. Subject jogs at 2.68m/s for 25 seconds
    ix. Subject runs at 3.33m/s for 20 seconds
    x. Subject walks at 1.34m/s for 15 seconds
    xi. Subject jogs at 2.68m/s for 25 seconds
    xii. Subject runs at 3.33m/s for 20 seconds
    xiii. Subject walks at 1.34m/s for 15 seconds
    xiv. Subject jogs at 2.68m/s for 25 seconds
    xv. Subject runs at 3.33m/s for 20 seconds
    xvi. Stop treadmill and record heart rate and RPE rating
    xvii. Subject steps off treadmill
    xviii. Subjects completes 1 minute of agility with reactive lights

e. Interval V
    i. Subject walks at 1.34m/s for 15 seconds
    ii. Subject jogs at 2.68m/s for 25 seconds
    iii. Subject runs at 3.33m/s for 20 seconds

iv. Subject walks at 1.34m/s for 15 seconds
v. Subject jogs at 2.68m/s for 25 seconds
vi. Subject runs at 3.33m/s for 20 seconds
vii. Subject walks at 1.34m/s for 15 seconds
viii. Subject jogs at 2.68m/s for 25 seconds
ix. Subject runs at 3.33m/s for 20 seconds
x. Subject walks at 1.34m/s for 15 seconds
xi. Subject jogs at 2.68m/s for 25 seconds
xii. Subject runs at 3.33m/s for 20 seconds
xiii. Subject walks at 1.34m/s for 15 seconds
xiv. Subject jogs at 2.68m/s for 25 seconds
xv. Subject runs at 3.33m/s for 20 seconds
xvi. Stop treadmill and record heart rate and RPE rating
xvii. Subject steps off treadmill
xviii. Subjects completes 1 minute of agility with reactive lights
xix. Record heart rate and RPE rating immediately after agility exercise
xx. Subject returns to treadmill
xxi. Collect walking
xxii. Collect running

Appendix D
Additional Results

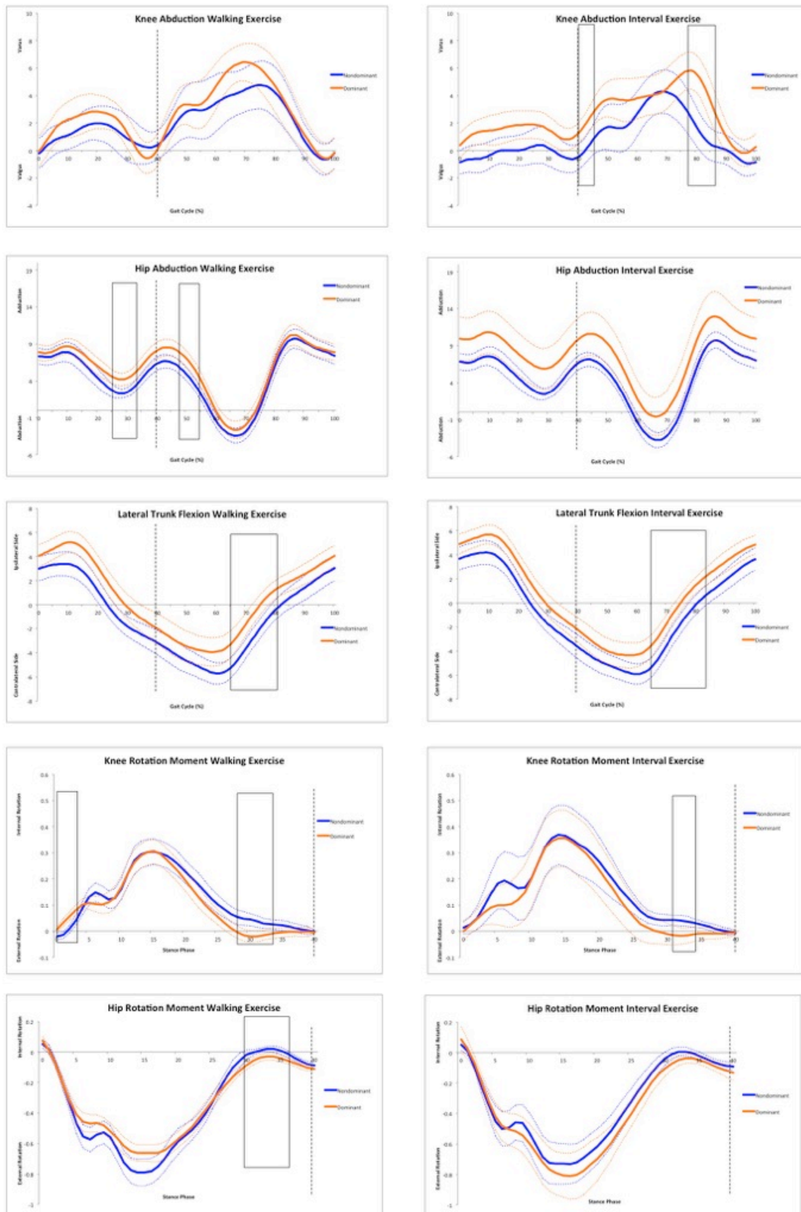


Figure D-1. Means and 90% confidence intervals for each limb for all subjects before the walking and interval exercise protocols. Areas in which confidence intervals did not overlap for three or more consecutive points were considered statistically significant. Toe-off during running gait is represented with a vertical dashed line. Dominant leg was defined as the preferred kicking leg. Kinematic data are presented in degrees and internal moments were normalized to mass (Nm/kg).

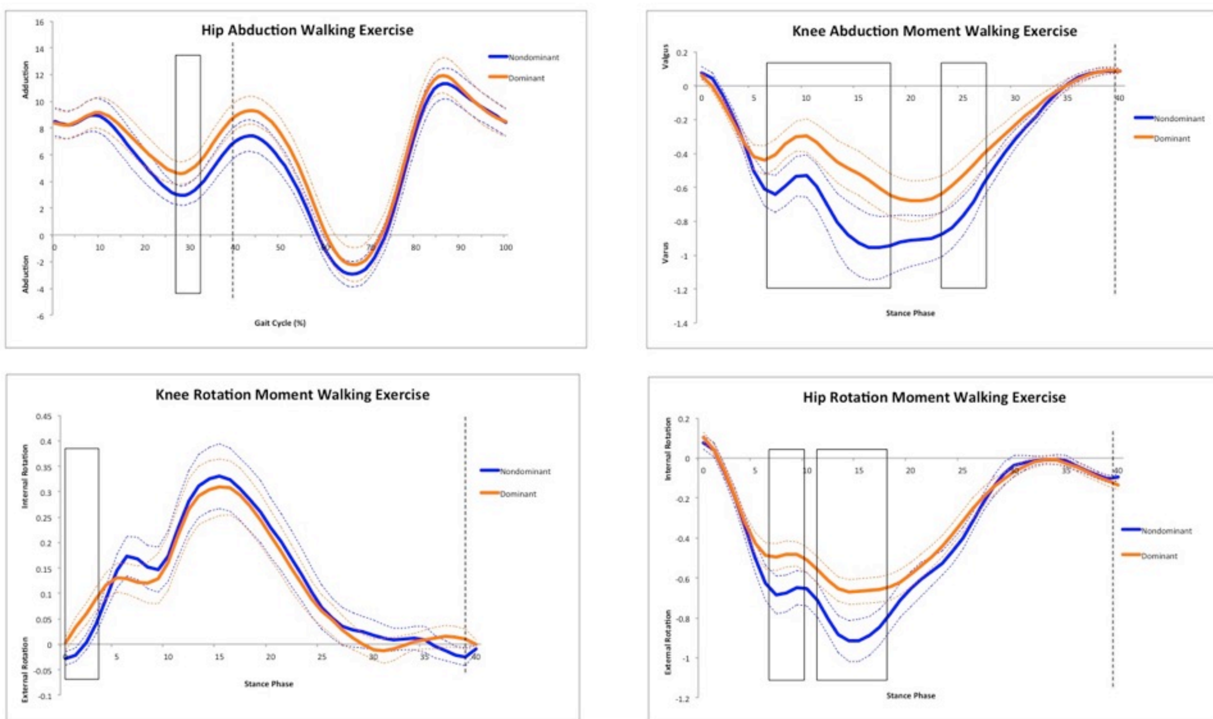


Figure D-2. Means and 90% confidence intervals for each limb for all subjects after the walking exercise protocol. Areas in which confidence intervals did not overlap for three or more consecutive points were considered statistically significant. Toe-off during running gait is represented with a vertical dashed line. Dominant leg was defined as the preferred kicking leg. Kinematic data are presented in degrees and internal moments were normalized to mass (Nm/kg). There were no differences between limbs after the Interval exercise protocol.

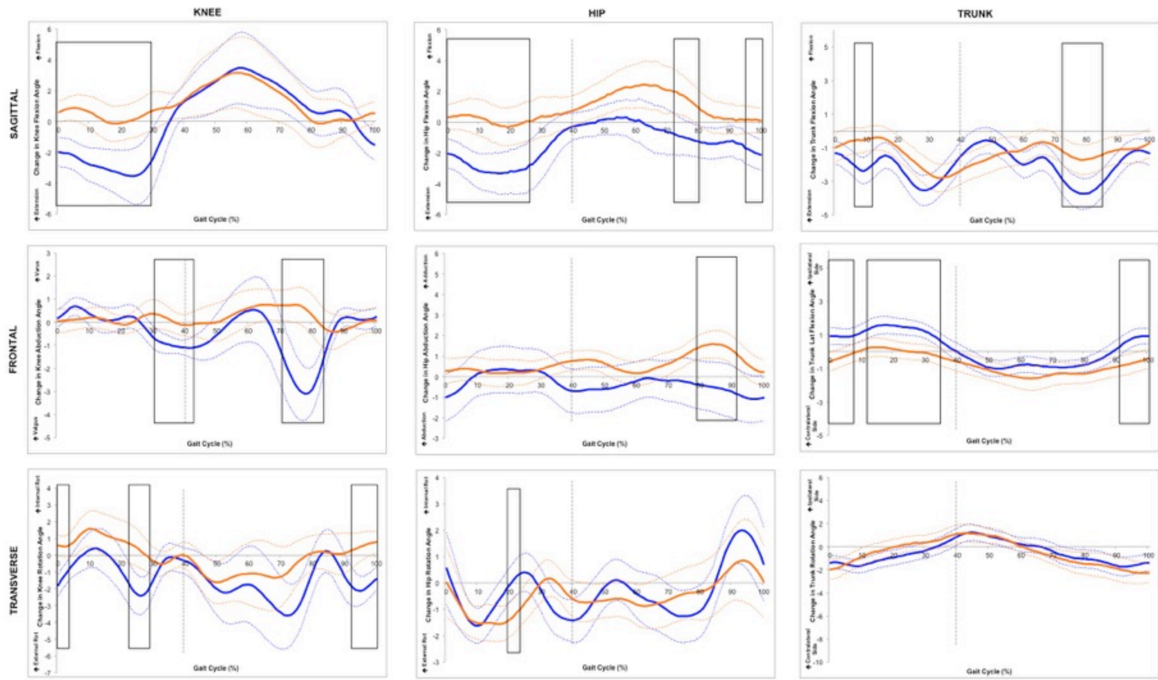


Figure D-3. Change in kinematics (degrees) in the high fit group after the walking exercise (orange) and the interval exercise (blue) with 90% confidence intervals over the entire gait cycle (0-100%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

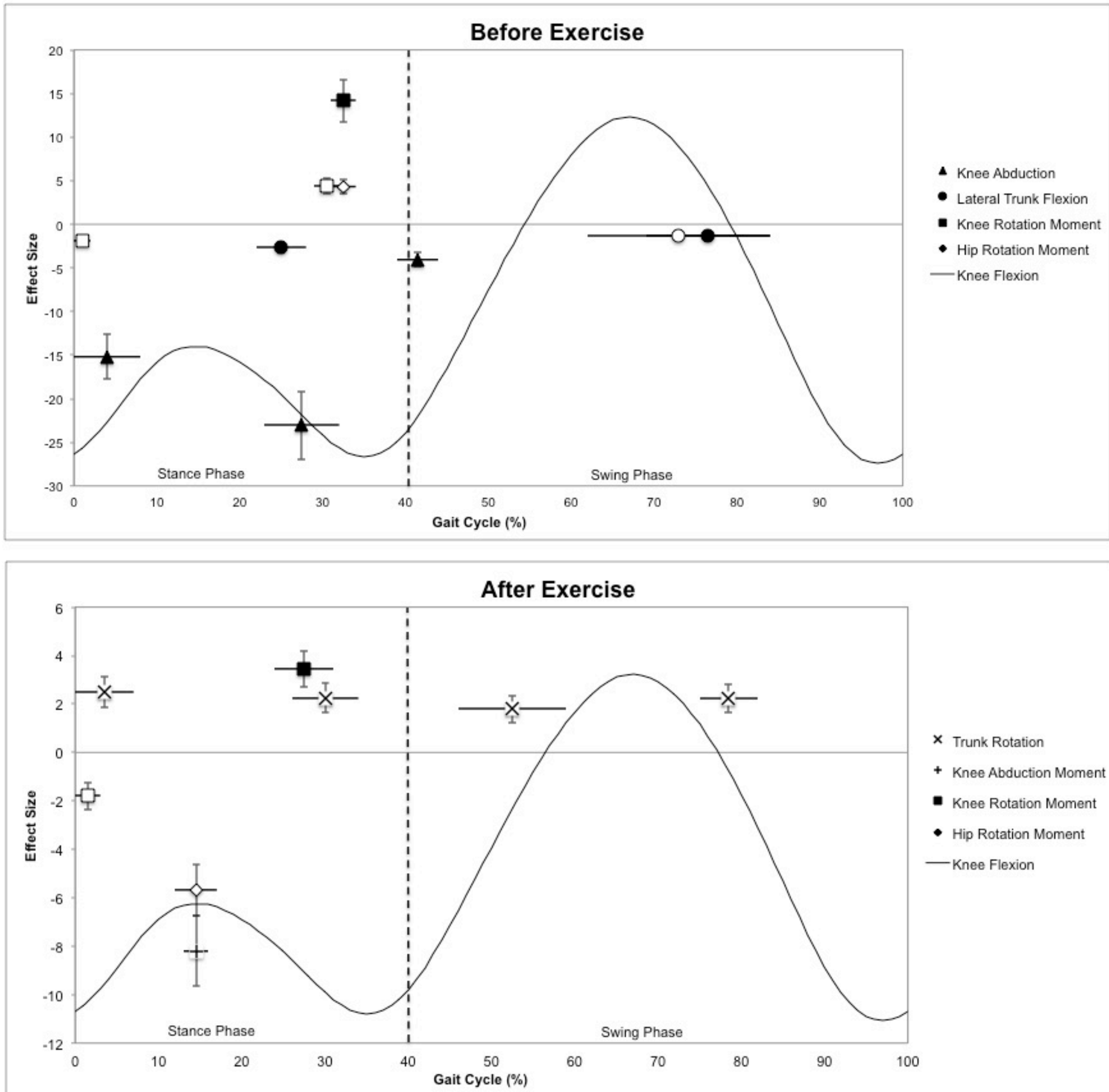
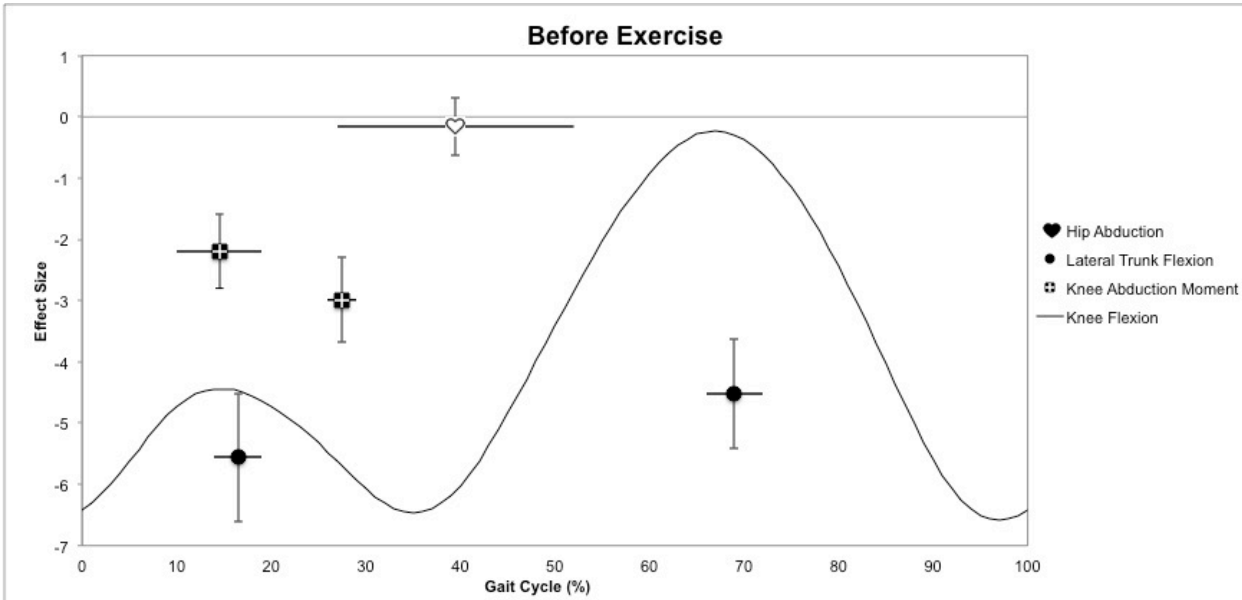


Figure D-4. Effect sizes for significant differences between dominant and nondominant limbs during the gait cycle in the high fit group before and after exercise. Vertical error bars represent 90% confidence intervals for the effect size point estimate. The horizontal line represents the duration across the gait cycle where confidence intervals did not overlap. Open shapes represent the Walking exercise and closed shapes represent the Interval exercise.



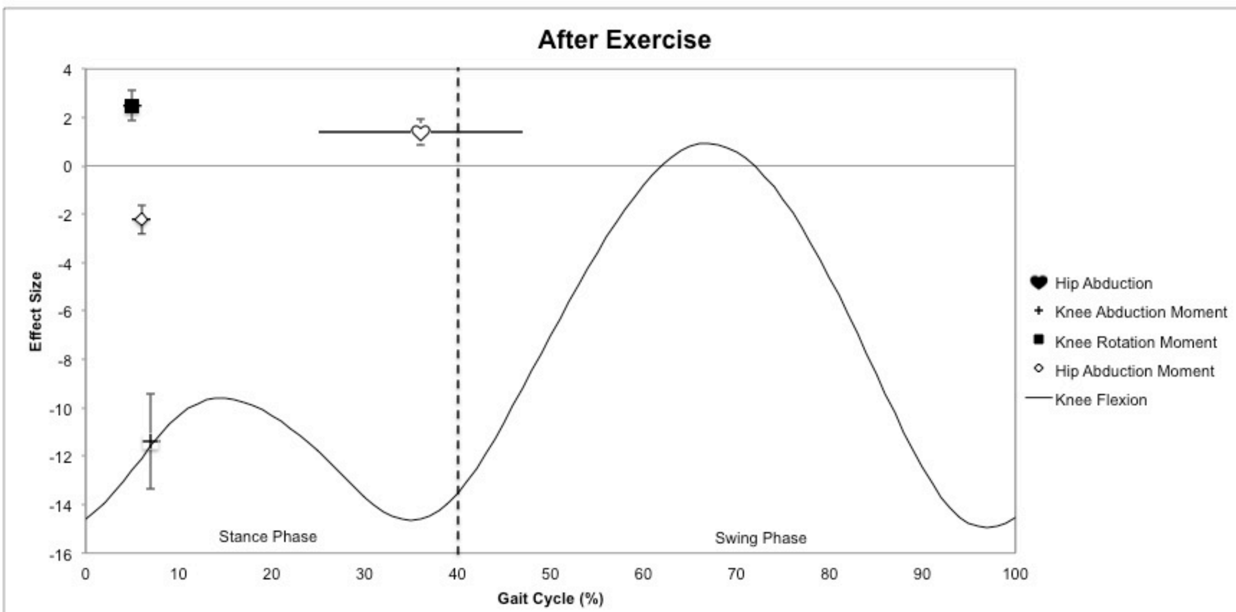


Figure D-5. Effect sizes for significant differences between dominant and nondominant limbs during the gait cycle in the low fit group before and after exercise. Vertical error bars represent 90% confidence intervals for the effect size point estimate. The horizontal line represents the duration across the gait cycle where confidence intervals did not overlap. Open shapes represent the Walking exercise and closed shapes represent the Interval exercise.

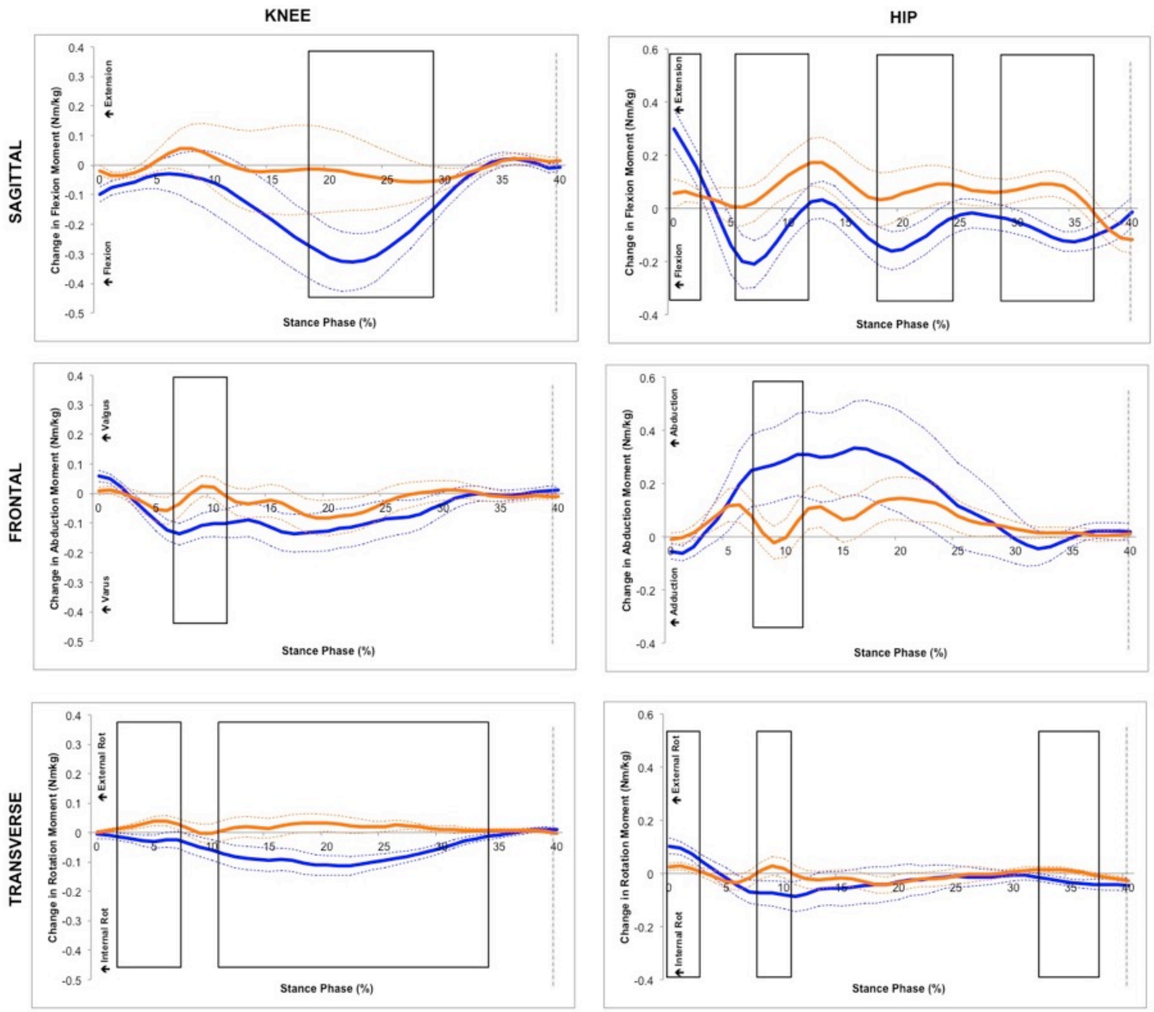


Figure D-6. Change in kinetics (Nm/kg) in the high fit group after the walking exercise (orange) and the interval exercise (blue) with 90% confidence intervals over the entire stance phase of gait (0-40%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

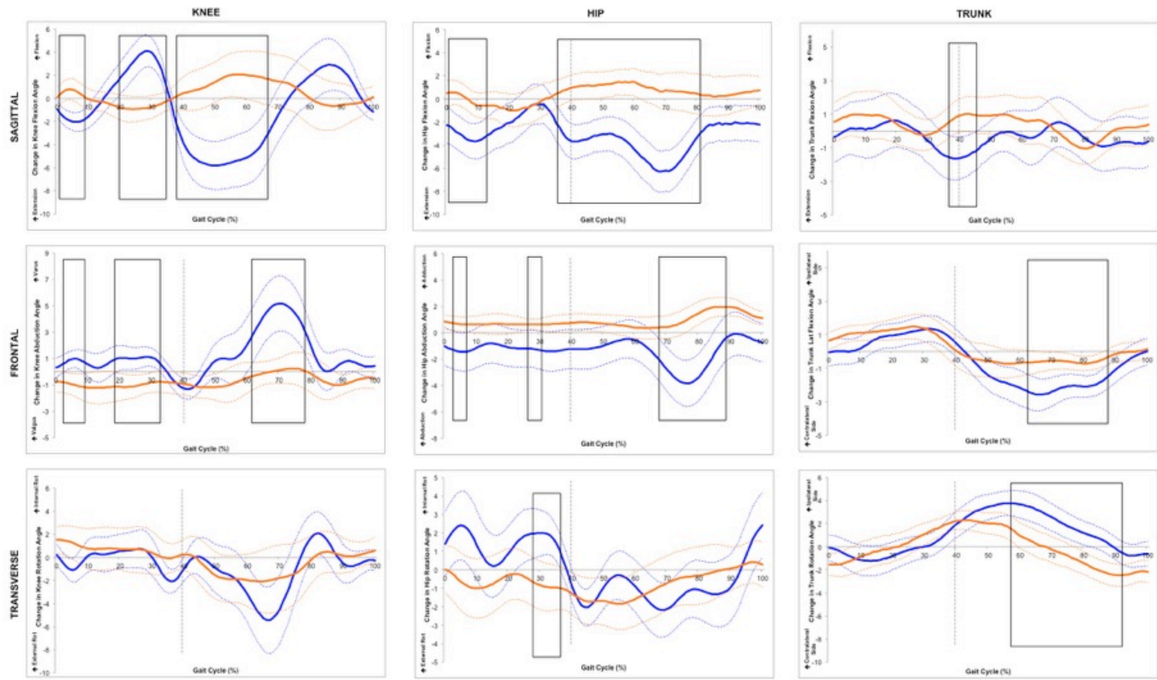


Figure D-7. Change in kinematics (degrees) in the low fit group after the walking exercise (orange) and the interval exercise (blue) with 90% confidence intervals over the entire gait cycle (0-100%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant

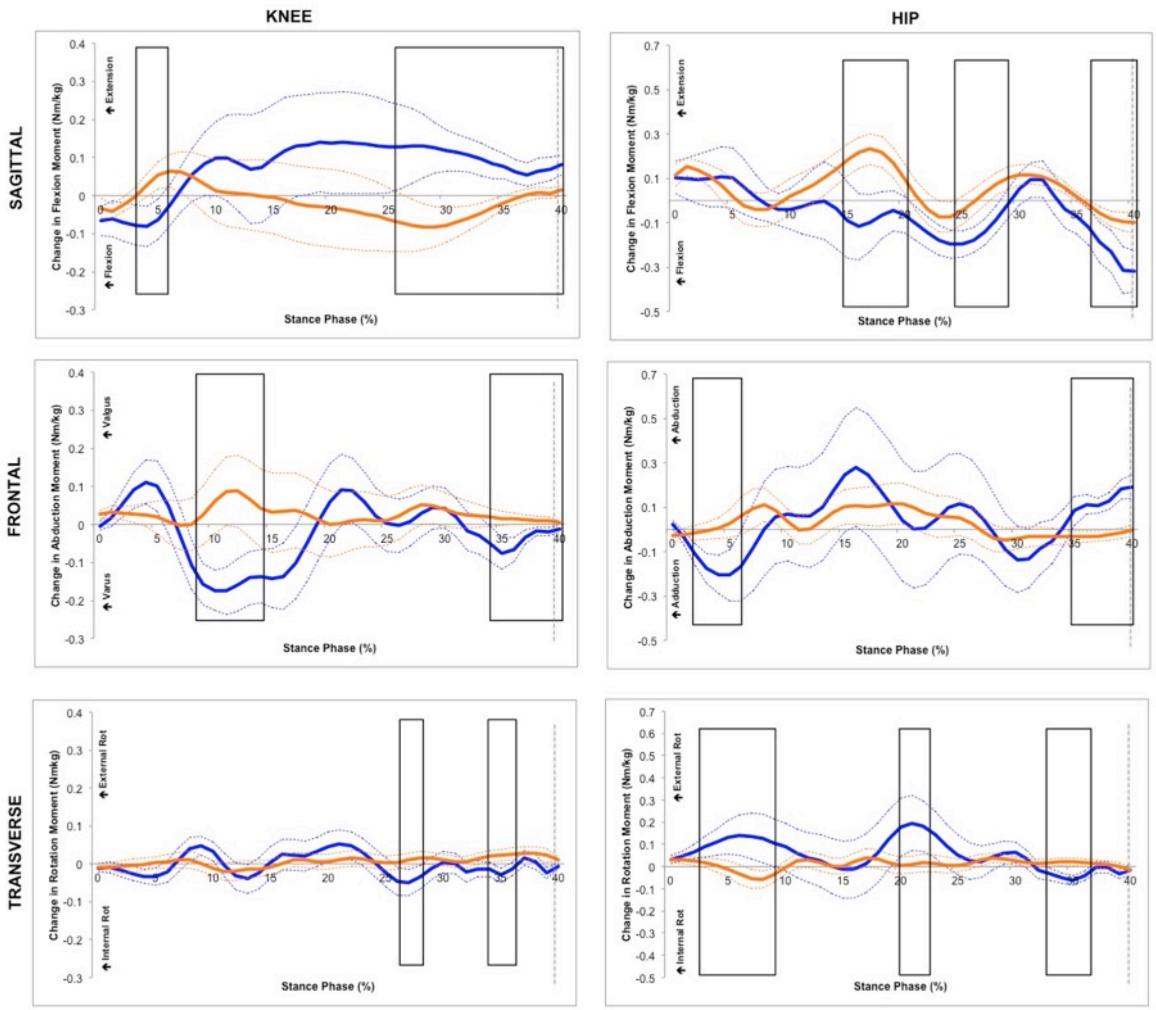


Figure D-8. Change in kinetics (Nm/kg) in the low fit group after the walking exercise (orange) and the interval exercise (blue) with 90% confidence intervals over the entire stance phase of gait (0-40%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

Table D-1. Mean differences, Cohen's *d* effect size and 90% confidence intervals (CI) for significantly different change scores between exercise protocols in the low fit group. Kinematics are presented in degrees and kinetics are moments normalized to body mass (Nm/kg).

	Variable	Gait Cycle	Mean Difference (90% CI)	Effect Size (90% CI)
KNEE	Knee Flexion	1-9%	-2.33 (0.19)	-9.25 (2.40)
		20-34%	3.86 (0.45)	6.27 (1.71)
		38-67%	-6.30 (2.65)	-1.75 (-0.92)
	Knee Adduction	2-9%	1.80 (0.09)	15.09 (3.81)
		18-32%	2.03 (0.09)	16.11 (4.06)
		61-78%	4.22 (0.45)	6.83 (1.83)
HIP	Hip Flexion	0-12%	-3.19 (0.36)	-6.57 (1.77)
		35-81%	-5.14 (0.65)	-5.79 (1.60)
	Hip Adduction	3-7%	-2.07 (0.10)	-14.60 (3.69)
		26-30%	-1.88 (0.10)	-13.78 (3.49)
		67-88%	-3.87 (0.62)	-4.59 (1.34)
	Hip Rotation	28-35%	2.74 (0.12)	17.46 (4.39)
TRUNK	Trunk Flexion	37-44%	-2.42 (0.10)	-17.66 (4.43)
	Lateral Trunk Flexion	62-88%	-1.57 (0.16)	-7.13 (1.90)
	Trunk Rotation	57-92%	2.64 (0.95)	2.05 (0.87)
KNEE	Knee Flexion Moment	3-6%	-0.10 (0.02)	-3.51 (1.12)
		26-40%	0.14 (0.02)	4.16 (1.25)
	Knee Adduction Moment	9-14%	-0.22 (0.02)	-10.41 (2.68)
		34-40%	-0.05 (0.01)	-2.82 (0.99)
	Knee Rotation Moment	27-29%	-0.05 (0.01)	-3.35 (1.09)
		34-37%	-0.04 (0.01)	-2.61 (0.95)
HIP	Hip Flexion Moment	15-21%	-0.25 (0.04)	-4.31 (1.28)
		25-29%	-0.15 (0.05)	-2.31 (0.90)
		36-40%	-0.16 (0.05)	-2.52 (0.94)
	Hip Adduction Moment	2-6%	-0.19 (0.02)	-5.51 (1.54)
		35-40%	0.16 (0.02)	5.05 (1.43)
	Hip Rotation Moment	3-9%	0.13 (0.02)	5.39 (1.51)
		20-23%	0.15 (0.01)	9.34 (2.42)
		33-37%	-0.06 (0.01)	-3.59 (1.13)

Table D-2. Mean differences, Cohen's *d* effect size and 90% confidence intervals (CI) for significantly different change scores between exercise protocols in the high fit group. Kinematics are presented in degrees and kinetics are moments normalized to body mass (Nm/kg).

	Variable	Gait Cycle	Mean Difference (90% CI)	Effect Size (90% CI)
KNEE	Knee Flexion	0-30%	-3.25 (0.30)	-7.29 (1.78)
	Knee Adduction	31-42%	-1.05 (0.10)	-6.99 (1.72)
		71-83%	-3.02 (0.29)	-7.08 (1.74)
	Knee Rotation	0-4%	-1.81 (0.20)	-5.97 (1.51)
		22-29%	-2.42 (0.21)	-7.64 (1.86)
		92-100%	-2.41 (0.14)	-11.19 (2.63)
HIP	Hip Flexion	0-25%	-3.05 (0.24)	-8.44 (2.03)
		72-80%	-2.58 (0.20)	-8.85 (2.12)
		95-100%	-2.05 (0.08)	-17.00 (3.93)
	Hip Adduction	79-91%	-2.02 (0.09)	-15.56 (3.61)
	Hip Rotation	19-23%	1.34 (0.14)	6.58 (1.63)
TRUNK	Trunk Flexion	6-12%	-1.68 (0.08)	-14.56 (3.38)
		73-85%	-1.91 (0.13)	-9.51 (2.26)
	Lateral Trunk Flexion	0-7%	1.26 (0.08)	10.46 (2.47)
		11-35%	1.28 (0.15)	5.60 (1.43)
		91-100%	1.39 (0.13)	7.28 (1.78)
KNEE	Knee Flexion Moment	18-29%	-0.23 (0.03)	-5.42 (1.39)
	Knee Adduction Moment	7-11%	-0.11 (0.01)	-5.69 (1.45)
	Knee Rotation Moment	2-8%	-0.05 (0.01)	-5.30 (1.37)
		11-34%	-0.10 (0.01)	-4.57 (1.23)
HIP	Hip Flexion Moment	0-2%	0.17 (0.03)	3.36 (1.00)
		6-12%	-0.20 (0.05)	-2.45 (0.85)
		18-25%	-0.17 (0.03)	-4.26 (1.17)
		29-37%	-0.15 (0.02)	-4.08 (1.13)
	Hip Adduction Moment	8-12%	0.26 (0.03)	6.45 (1.61)
	Hip Rotation Moment	0-3%	0.06 (0.01)	2.80 (0.91)
		8-11%	-0.09 (0.01)	-8.35 (2.01)
		32-38%	-0.04 (0.01)	-3.35 (1.00)

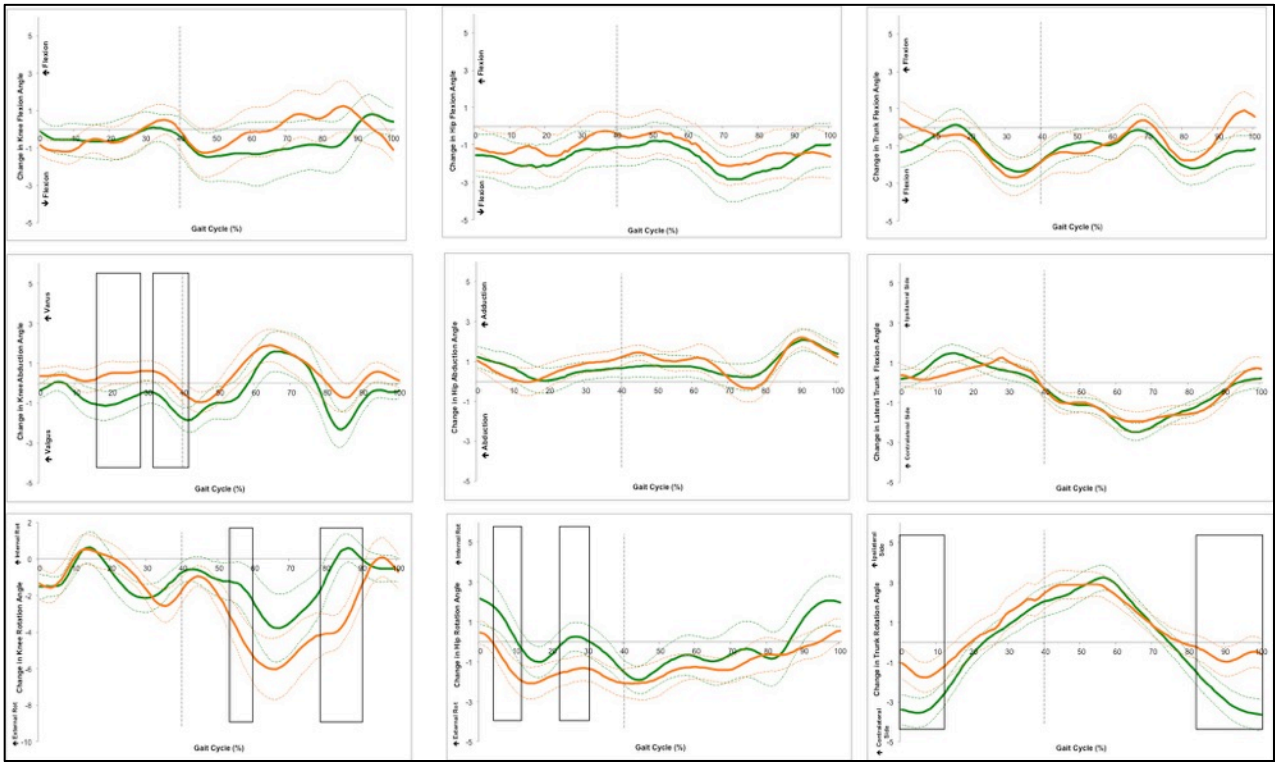


Figure D-9. Change in kinematics (degrees) after exercise in patients with ACL reconstruction within 12 months (green) and more than 12 months (orange) with 90% confidence intervals over the entire gait cycle (0-100%). Toe-off during running gait is represented by the dashed vertical line. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

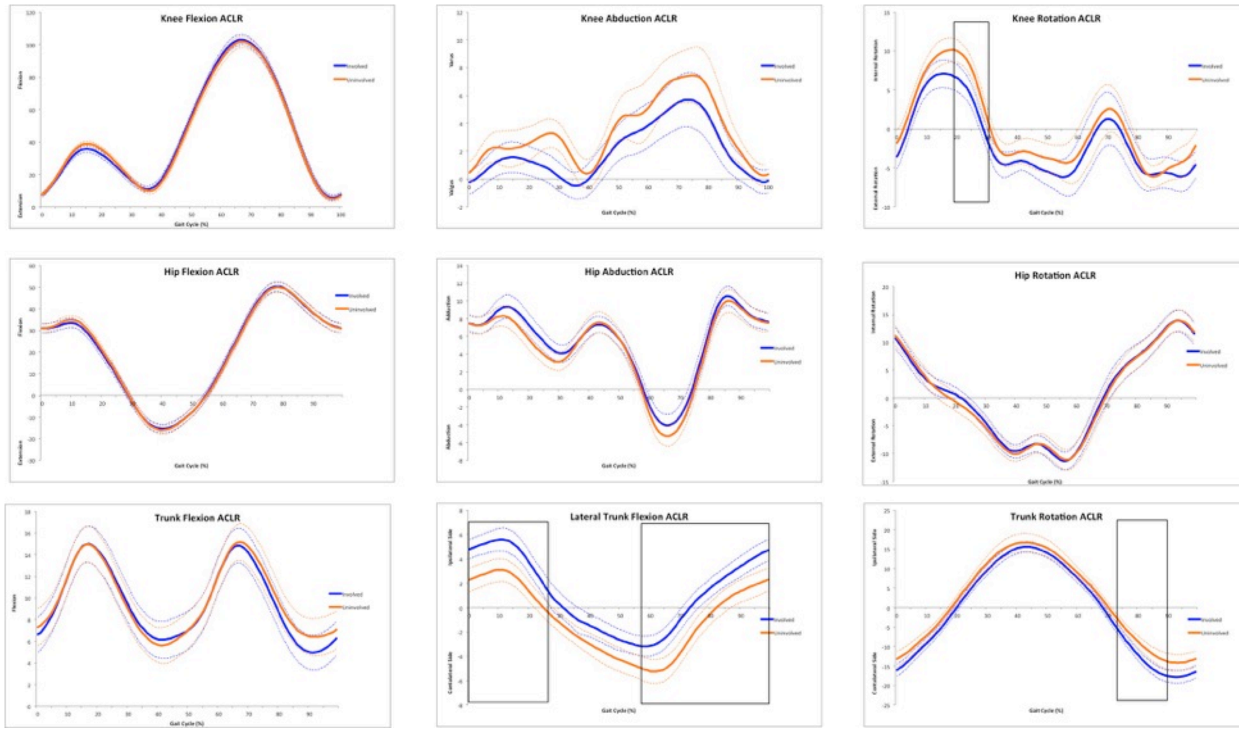


Figure D-10. Limb differences in kinematics (degrees) before exercise in patients with ACL reconstruction with 90% confidence intervals over the entire gait cycle (0-100%). The involved limb is in blue and uninvolved limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

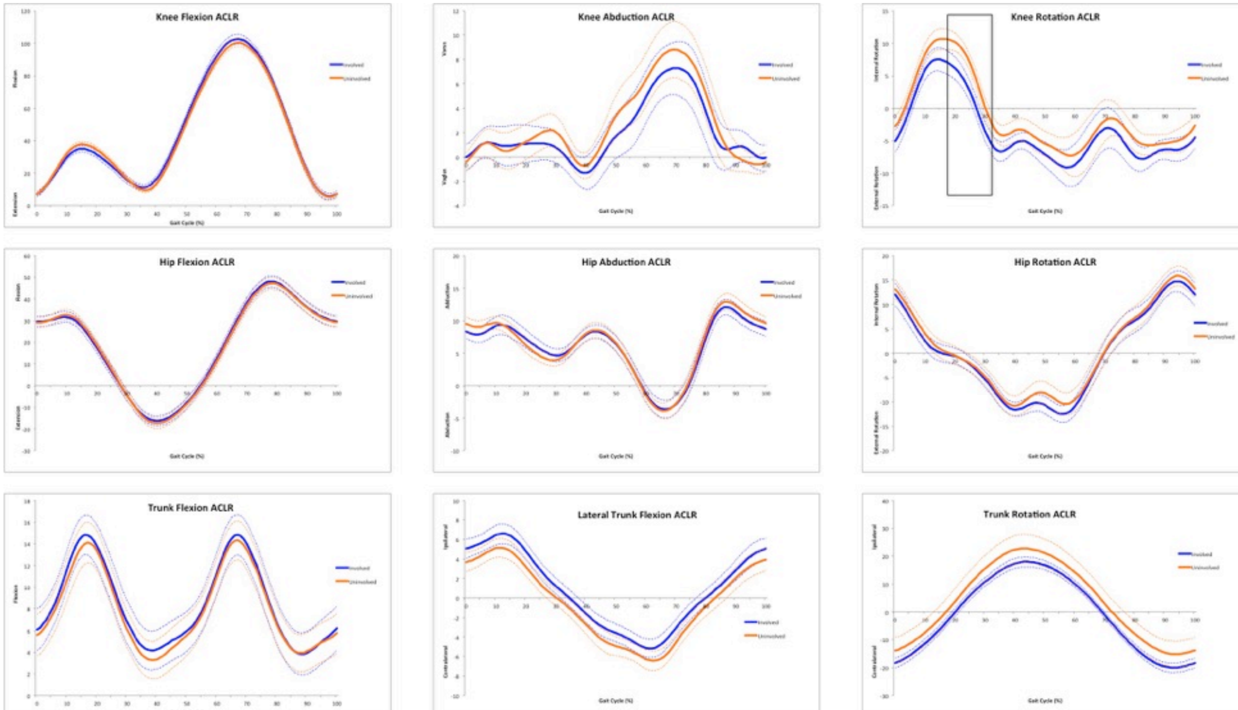


Figure D-11. Limb differences in kinematics (degrees) after exercise in patients with ACL reconstruction with 90% confidence intervals over the entire gait cycle (0-100%). The involved limb is in blue and uninvolved limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

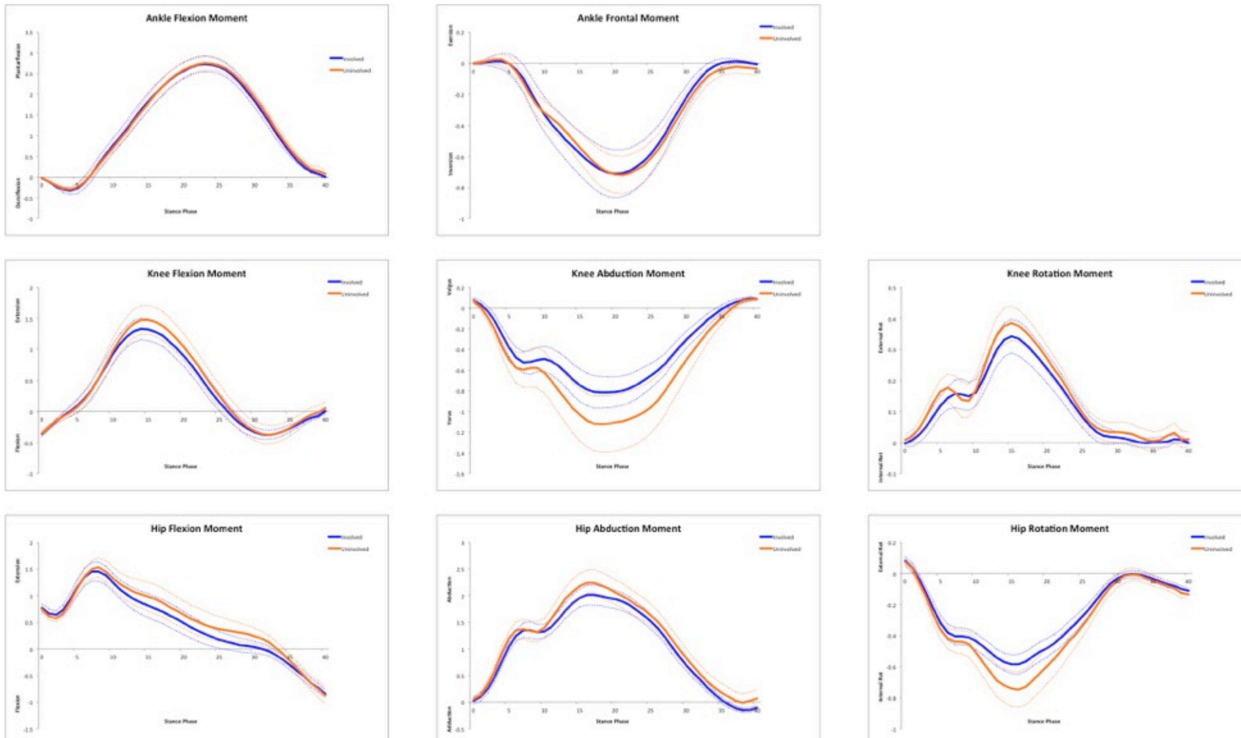


Figure D-12. Limb differences in kinetics (Nm/kg) before exercise in patients with ACL reconstruction with 90% confidence intervals over the entire stance phase of gait (0-40%). The involved limb is in blue and uninvolved limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

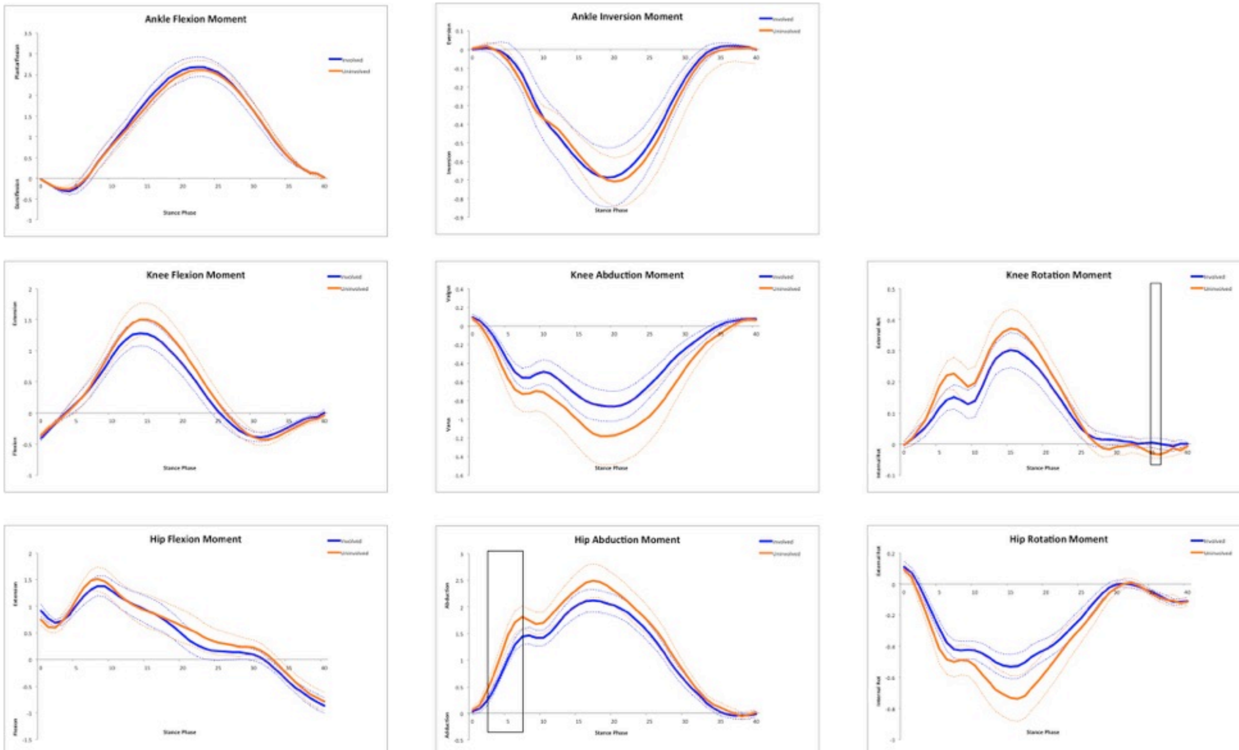


Figure D-13. Limb differences in kinetics (Nm/kg) after exercise in patients with ACL reconstruction with 90% confidence intervals over the entire stance phase of gait (0-40%). The involved limb is in blue and uninvolved limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

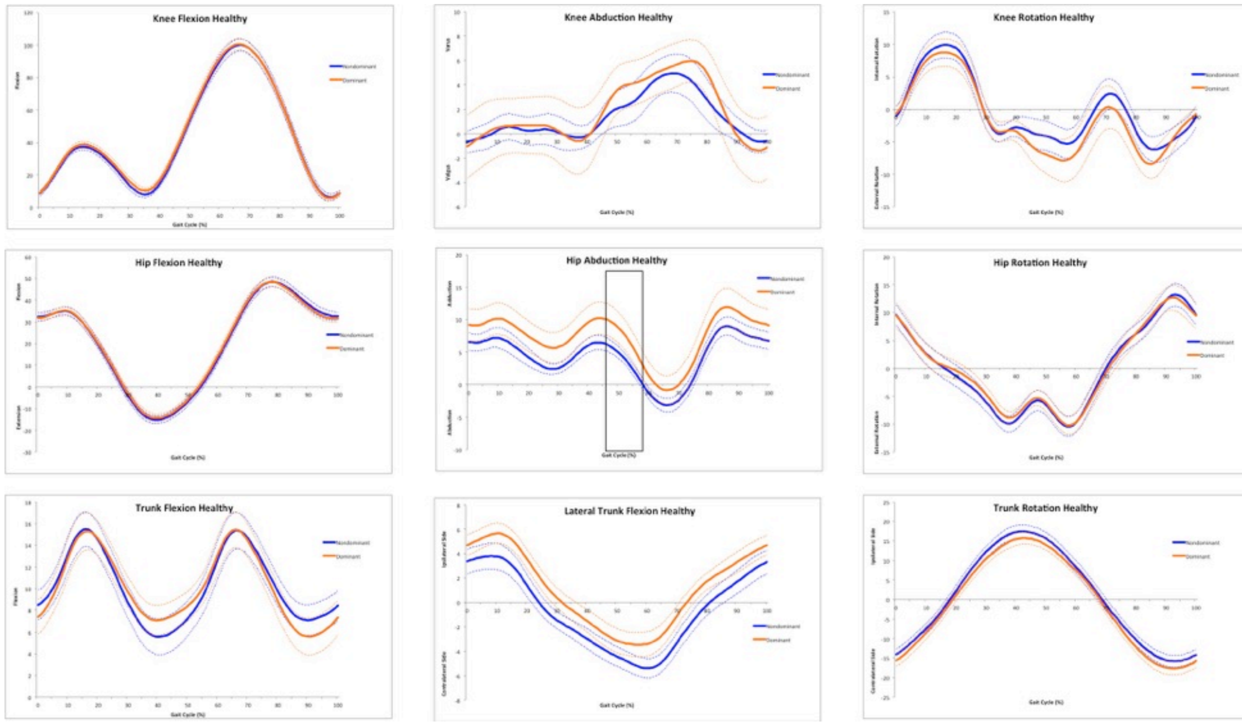


Figure D-14. Limb differences in kinematics (degrees) before exercise in healthy individuals with 90% confidence intervals over the entire gait cycle (0-100%). The nondominant limb is in blue and dominant limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

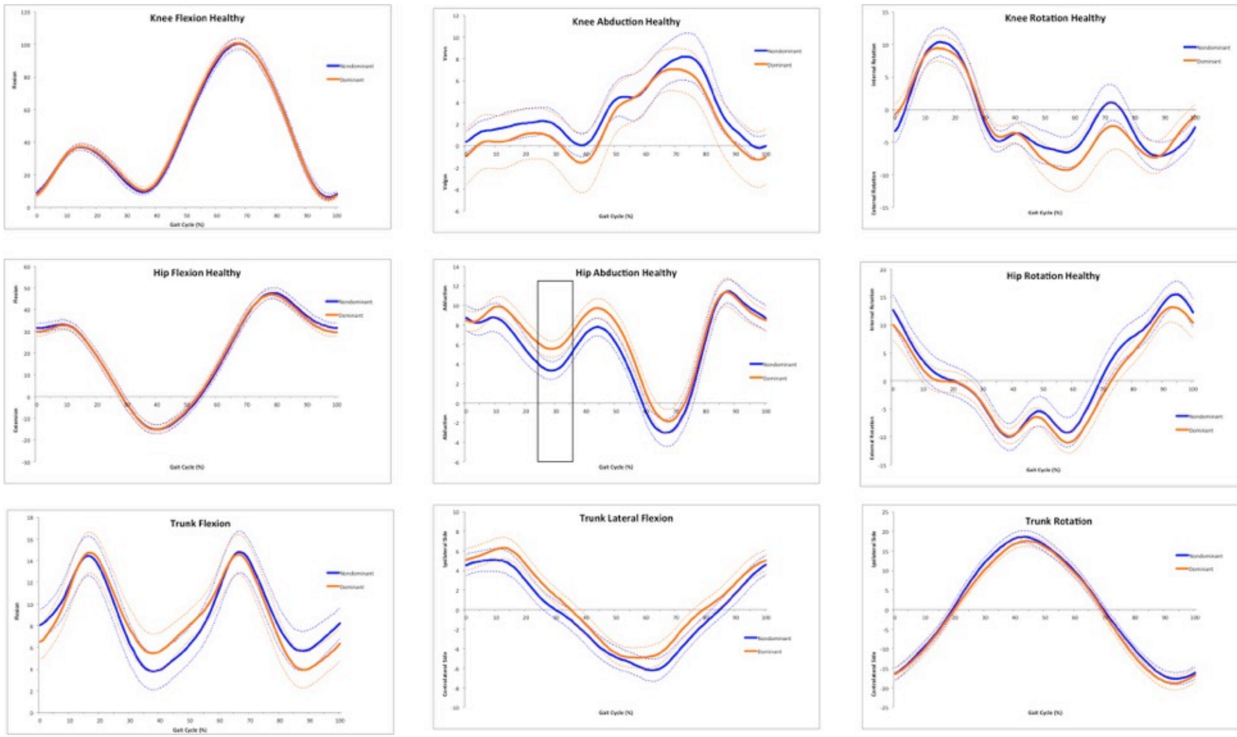


Figure D-15. Limb differences in kinematics (degrees) after exercise in healthy individuals with 90% confidence intervals over the entire gait cycle (0-100%). The nondominant limb is in blue and dominant limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

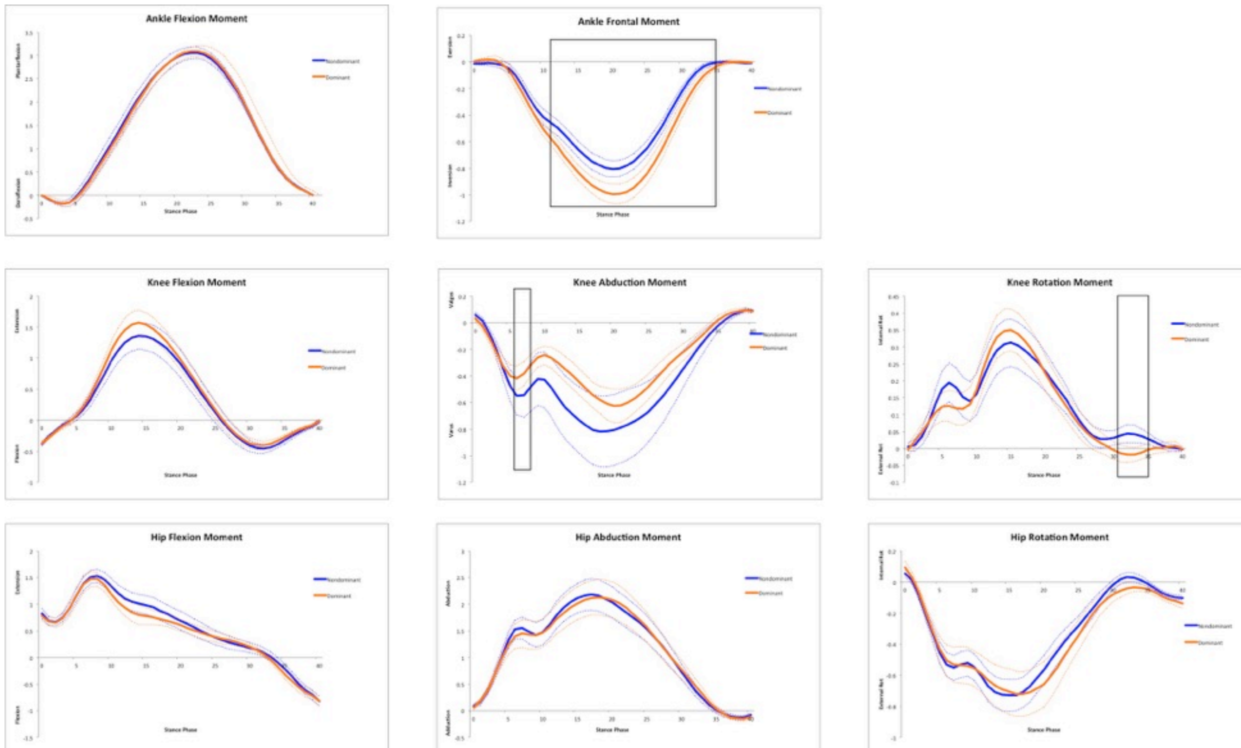


Figure D-16. Limb differences in kinetics (Nm/kg) before exercise in healthy individuals with 90% confidence intervals over the entire gait cycle (0-100%). The nondominant limb is in blue and dominant limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

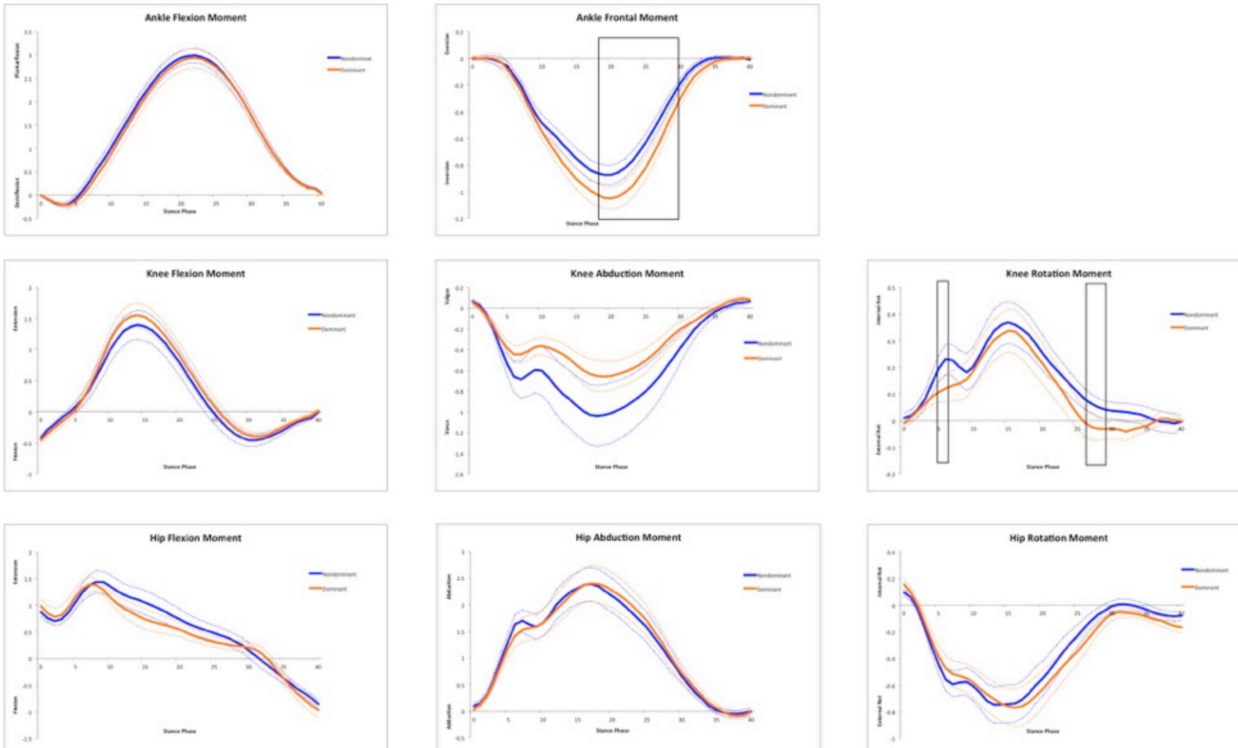


Figure D-17. Limb differences in kinetics (Nm/kg) after exercise in healthy individuals with 90% confidence intervals over the entire gait cycle (0-100%). The nondominant limb is in blue and dominant limb is in orange. Areas in which confidence intervals did not overlap for three or more points were considered statistically significant.

Table D-3. Bivariate correlations between side-to-side differences in running kinematics and knee extensor and flexor strength symmetry.

Correlations

		180PkTrq_LSI_Ext	180PkTrq_LSI_Flex	180Work_LSI_Ext	180Work_LSI_Flex	180Power_LSI_Ext	180Power_LSI_Flex	180Time_PkTrq_LSI_Ext	180Time_PkTrq_LSI_Flex
KNEE_FLEX_DIFF_PRE	Pearson Correlation	.279	-.214	.216	-.159	.243	-.149	.111	-.036
	Sig. (2-tailed)	.116	.232	.226	.378	.173	.409	.539	.840
	N	33	33	33	33	33	33	33	33
KNEE_ABD_DIFF_PRE	Pearson Correlation	.203	.034	.304	.122	.343	.125	.138	-.065
	Sig. (2-tailed)	.256	.850	.085	.500	.051	.489	.445	.720
	N	33	33	33	33	33	33	33	33
KNEE_ROT_DIFF_PRE	Pearson Correlation	.197	.001	.198	.246	.204	.226	.031	-.011
	Sig. (2-tailed)	.271	.997	.270	.168	.255	.206	.866	.951
	N	33	33	33	33	33	33	33	33
HIP_FLEX_DIFF_PRE	Pearson Correlation	.444**	-.027	.360*	-.101	.360*	-.110	.199	.049
	Sig. (2-tailed)	.010	.881	.040	.575	.039	.542	.267	.786
	N	33	33	33	33	33	33	33	33
HIP_ABD_DIFF_PRE	Pearson Correlation	-.078	.004	.033	-.005	-.002	-.021	.327	-.154
	Sig. (2-tailed)	.666	.982	.855	.977	.992	.909	.063	.393
	N	33	33	33	33	33	33	33	33
HIP_ROT_DIFF_PRE	Pearson Correlation	.132	.275	.337	.341	.330	.334	.268	-.198
	Sig. (2-tailed)	.463	.121	.055	.052	.061	.057	.132	.269
	N	33	33	33	33	33	33	33	33
TRUNK_FLEX_DIFF_PRE	Pearson Correlation	-.351*	-.064	-.416*	-.212	-.514**	-.243	.161	.078
	Sig. (2-tailed)	.045	.722	.016	.235	.002	.174	.370	.667
	N	33	33	33	33	33	33	33	33
TRUNK_LF_DIFF_PRE	Pearson Correlation	-.271	-.163	-.308	-.175	-.253	-.126	-.221	.047
	Sig. (2-tailed)	.127	.365	.081	.329	.156	.483	.217	.797
	N	33	33	33	33	33	33	33	33
TRUNK_ROT_DIFF_PRE	Pearson Correlation	.111	-.178	.064	-.096	.097	-.062	.025	.418*
	Sig. (2-tailed)	.537	.321	.722	.595	.590	.732	.890	.015
	N	33	33	33	33	33	33	33	33
vGRF_DIFF_PRE	Pearson Correlation	.616**	.268	.527**	.258	.562**	.214	-.084	.045
	Sig. (2-tailed)	.000	.132	.002	.146	.001	.231	.642	.804
	N	33	33	33	33	33	33	33	33

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-4. Bivariate correlations between side-to-side differences in running kinematics and symmetry on functional performance.

Correlations

		SL_LSI	SqHop_Time_LSI_PRE	SqHop_GCT_LSI_PRE
KNEE_FLEX_DIFF_PRE	Pearson Correlation	.251	.213	.179
	Sig. (2-tailed)	.159	.235	.318
	N	33	33	33
KNEE_ABD_DIFF_PRE	Pearson Correlation	.298	-.359*	-.112
	Sig. (2-tailed)	.092	.040	.536
	N	33	33	33
KNEE_ROT_DIFF_PRE	Pearson Correlation	.244	.153	.201
	Sig. (2-tailed)	.172	.396	.261
	N	33	33	33
HIP_FLEX_DIFF_PRE	Pearson Correlation	.120	-.078	-.147
	Sig. (2-tailed)	.506	.667	.416
	N	33	33	33
HIP_ABD_DIFF_PRE	Pearson Correlation	-.026	.246	.193
	Sig. (2-tailed)	.884	.168	.282
	N	33	33	33
HIP_ROT_DIFF_PRE	Pearson Correlation	.152	.063	.216
	Sig. (2-tailed)	.398	.727	.228
	N	33	33	33
TRUNK_FLEX_DIFF_PRE	Pearson Correlation	-.245	.337	.219
	Sig. (2-tailed)	.170	.055	.221
	N	33	33	33
TRUNK_LF_DIFF_PRE	Pearson Correlation	-.215	.075	.109
	Sig. (2-tailed)	.230	.680	.545
	N	33	33	33
TRUNK_ROT_DIFF_PRE	Pearson Correlation	.066	-.316	-.349*
	Sig. (2-tailed)	.717	.073	.046
	N	33	33	33
vGRF_DIFF_PRE	Pearson Correlation	.414*	-.051	.000
	Sig. (2-tailed)	.017	.777	.999
	N	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-5. Bivariate correlations between side-to-side differences in running kinetics and knee extensor and flexor strength symmetry.

Correlations

		180PkTrq_LSI_Ext	180PkTrq_LSI_Flex	180Work_LSI_Ext	180Work_LSI_Flex	180Power_LSI_Ext	180Power_LSI_Flex	180Time_PkTrq_LSI_Ext	180Time_PkTrq_LSI_Flex
KNEE_FLEX_MOM_DIFF	Pearson Correlation	.155	.065	-.058	-.091	-.016	-.105	-.311	.106
	Sig. (2-tailed)	.390	.719	.749	.615	.931	.563	.078	.557
	N	33	33	33	33	33	33	33	33
KNEE_ABD_MOM_DIFF	Pearson Correlation	.037	.004	-.148	-.016	-.073	.019	-.055	-.152
	Sig. (2-tailed)	.838	.981	.411	.932	.686	.917	.762	.398
	N	33	33	33	33	33	33	33	33
KNEE_ROT_MOM_DIFF	Pearson Correlation	-.189	-.082	-.059	-.078	-.112	-.104	-.052	.195
	Sig. (2-tailed)	.293	.649	.745	.666	.537	.564	.772	.278
	N	33	33	33	33	33	33	33	33
HIP_FLEX_MOM_DIFF	Pearson Correlation	.076	.039	.343	.203	.275	.189	.497**	-.072
	Sig. (2-tailed)	.676	.830	.051	.257	.121	.293	.003	.691
	N	33	33	33	33	33	33	33	33
HIP_ABD_MOM_DIFF	Pearson Correlation	-.226	-.069	-.003	.039	-.075	.020	.052	.179
	Sig. (2-tailed)	.205	.703	.989	.831	.678	.912	.776	.320
	N	33	33	33	33	33	33	33	33
HIP_ROT_MOM_DIFF	Pearson Correlation	.097	.103	-.046	.036	.040	.072	-.051	-.155
	Sig. (2-tailed)	.590	.570	.799	.841	.825	.689	.777	.389
	N	33	33	33	33	33	33	33	33

**. Correlation is significant at the 0.01 level (2-tailed).

Table D-6. Bivariate correlations between side-to-side differences in running kinetics and symmetry on functional performance.

Correlations

		SqHop_Time_LSI_PRE	SqHop_GCT_LSI_PRE	SL_LSI
KNEE_FLEX_MOM_DIFF	Pearson Correlation	-.167	-.128	.171
	Sig. (2-tailed)	.353	.479	.343
	N	33	33	33
KNEE_ABD_MOM_DIFF	Pearson Correlation	-.122	-.020	-.003
	Sig. (2-tailed)	.500	.911	.985
	N	33	33	33
KNEE_ROT_MOM_DIFF	Pearson Correlation	.103	.002	-.142
	Sig. (2-tailed)	.568	.993	.430
	N	33	33	33
HIP_FLEX_MOM_DIFF	Pearson Correlation	.158	.102	-.173
	Sig. (2-tailed)	.381	.572	.334
	N	33	33	33
HIP_ABD_MOM_DIFF	Pearson Correlation	.187	.144	-.151
	Sig. (2-tailed)	.296	.425	.402
	N	33	33	33
HIP_ROT_MOM_DIFF	Pearson Correlation	-.047	-.010	.082
	Sig. (2-tailed)	.793	.954	.648
	N	33	33	33

Table D-7. Bivariate correlations between kinematic changes during running in the involved limb before and after exercise and knee extensor and flexor strength symmetry.

Correlations

		180PkTrq_LSI_Ext	180PkTrq_LSI_Flex	180Work_LSI_Ext	180Work_LSI_Flex	180Power_LSI_Ext	180Power_LSI_Flex	180Time_PkTrq_LSI_Ext	180Time_PkTrq_LSI_Flex
Knee_Flex_Inv_SS_Change	Pearson Correlation	-.055	.082	-.012	.075	-.133	-.012	-.066	-.136
	Sig. (2-tailed)	.761	.649	.946	.680	.461	.948	.714	.449
	N	33	33	33	33	33	33	33	33
Knee_Abd_Inv_SS_Change	Pearson Correlation	-.156	-.148	-.099	-.048	-.176	-.086	.105	.294
	Sig. (2-tailed)	.384	.412	.585	.792	.328	.633	.560	.096
	N	33	33	33	33	33	33	33	33
Knee_Rot_Inv_SS_Change	Pearson Correlation	.033	.108	-.090	-.136	-.098	-.132	-.208	-.183
	Sig. (2-tailed)	.855	.548	.617	.450	.586	.464	.246	.307
	N	33	33	33	33	33	33	33	33
Hip_Flex_Inv_SS_Change	Pearson Correlation	.116	.008	.044	.055	-.014	.003	.023	-.048
	Sig. (2-tailed)	.520	.966	.809	.762	.940	.988	.899	.792
	N	33	33	33	33	33	33	33	33
Hip_Abd_Inv_SS_Change	Pearson Correlation	-.024	-.238	-.026	-.105	.035	-.074	-.263	-.088
	Sig. (2-tailed)	.894	.182	.885	.561	.845	.683	.140	.626
	N	33	33	33	33	33	33	33	33
Hip_Rot_Inv_SS_Change	Pearson Correlation	.059	-.135	-.065	-.137	-.047	-.150	-.236	.085
	Sig. (2-tailed)	.746	.452	.720	.446	.796	.405	.186	.639
	N	33	33	33	33	33	33	33	33
Trunk_Flex_Inv_SS_Change	Pearson Correlation	-.044	-.033	-.005	-.030	-.091	-.069	.286	-.046
	Sig. (2-tailed)	.809	.853	.979	.868	.615	.705	.107	.798
	N	33	33	33	33	33	33	33	33
Lat_Trunk_Flex_Inv_SS_Change	Pearson Correlation	.129	.212	.114	.084	.111	.051	-.064	-.137
	Sig. (2-tailed)	.474	.236	.528	.642	.538	.776	.726	.447
	N	33	33	33	33	33	33	33	33
Trunk_Rot_Inv_SS_Change	Pearson Correlation	.097	.166	.097	.042	.031	.014	.181	.118
	Sig. (2-tailed)	.590	.356	.590	.817	.866	.939	.314	.512
	N	33	33	33	33	33	33	33	33
vGRF_Inv_SS_Change	Pearson Correlation	-.143	-.103	-.220	-.197	-.097	-.121	-.040	-.139
	Sig. (2-tailed)	.426	.569	.220	.272	.591	.501	.827	.442
	N	33	33	33	33	33	33	33	33

Table D-8. Bivariate correlations between kinematic changes during running in the involved limb before and after exercise and symmetry on functional performance.

Correlations

		SqHop_Time_LSI_PRE	SqHop_GCT_LSI_PRE	SL_LSI
Knee_Flex_Inv_SS_Change	Pearson Correlation	.030	.167	.023
	Sig. (2-tailed)	.867	.352	.897
	N	33	33	33
Knee_Abd_Inv_SS_Change	Pearson Correlation	.309	.132	-.197
	Sig. (2-tailed)	.080	.466	.271
	N	33	33	33
Knee_Rot_Inv_SS_Change	Pearson Correlation	.034	.148	.139
	Sig. (2-tailed)	.850	.411	.439
	N	33	33	33
Hip_Flex_Inv_SS_Change	Pearson Correlation	-.364*	-.244	.093
	Sig. (2-tailed)	.037	.172	.605
	N	33	33	33
Hip_Abd_Inv_SS_Change	Pearson Correlation	-.178	-.146	-.073
	Sig. (2-tailed)	.321	.417	.688
	N	33	33	33
Hip_Rot_Inv_SS_Change	Pearson Correlation	.139	-.012	.028
	Sig. (2-tailed)	.441	.946	.877
	N	33	33	33
Trunk_Flex_Inv_SS_Change	Pearson Correlation	-.194	.023	-.006
	Sig. (2-tailed)	.278	.900	.972
	N	33	33	33
Lat_Trunk_Flex_Inv_SS_Change	Pearson Correlation	.035	.023	.197
	Sig. (2-tailed)	.848	.898	.272
	N	33	33	33
Trunk_Rot_Inv_SS_Change	Pearson Correlation	.047	.123	-.063
	Sig. (2-tailed)	.793	.496	.730
	N	33	33	33
vGRF_Inv_SS_Change	Pearson Correlation	-.003	-.109	-.044
	Sig. (2-tailed)	.985	.545	.810
	N	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-9. Bivariate correlations between kinetic changes during running in the involved limb before and after exercise and knee extensor and flexor strength symmetry.

Correlations

		180PkTrq_LSI_Ext	180PkTrq_LSI_Flex	180Work_LSI_Ext	180Work_LSI_Flex	180Power_LSI_Ext	180Power_LSI_Flex	180Time_PkTrq_LSI_Ext	180Time_PkTrq_LSI_Flex
Ankle_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.160	.135	-.102	.106	-.136	.061	-.066	.034
	Sig. (2-tailed)	.373	.452	.571	.557	.450	.737	.713	.850
	N	33	33	33	33	33	33	33	33
Ankle_Inv_Mom_Inv_SS_Change	Pearson Correlation	-.037	-.054	.184	.178	.063	.115	.585**	-.024
	Sig. (2-tailed)	.838	.765	.306	.323	.729	.523	.000	.893
	N	33	33	33	33	33	33	33	33
Knee_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.187	-.083	-.048	-.093	-.117	-.113	.161	.139
	Sig. (2-tailed)	.297	.647	.792	.607	.516	.530	.369	.439
	N	33	33	33	33	33	33	33	33
Knee_Abd_Mom_Inv_SS_Change	Pearson Correlation	.157	-.032	.145	-.139	.134	-.115	.296	.045
	Sig. (2-tailed)	.384	.862	.421	.439	.456	.524	.095	.803
	N	33	33	33	33	33	33	33	33
Knee_Rot_Mom_Inv_SS_Change	Pearson Correlation	.174	.219	.180	.334	.150	.316	-.055	.373*
	Sig. (2-tailed)	.333	.221	.317	.057	.403	.073	.762	.033
	N	33	33	33	33	33	33	33	33
Hip_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.075	-.082	-.132	-.060	-.180	-.096	.125	.089
	Sig. (2-tailed)	.677	.651	.465	.739	.316	.594	.487	.621
	N	33	33	33	33	33	33	33	33
Hip_Abd_Mom_Inv_SS_Change	Pearson Correlation	-.187	-.086	-.196	-.120	-.248	-.157	-.104	.121
	Sig. (2-tailed)	.296	.634	.275	.506	.164	.382	.563	.502
	N	33	33	33	33	33	33	33	33
Hip_Rot_Mom_Inv_SS_Change	Pearson Correlation	.041	.177	.169	.146	.247	.195	-.131	-.154
	Sig. (2-tailed)	.822	.324	.348	.418	.166	.276	.467	.391
	N	33	33	33	33	33	33	33	33

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-10. Bivariate correlations between kinetic changes during running in the involved limb before and after exercise and symmetry on functional performance.

Correlations

		SqHop_Time_LSI_PRE	SqHop_GCT_LSI_PRE	SL_LSI
Ankle_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.175	-.156	-.059
	Sig. (2-tailed)	.331	.385	.743
	N	33	33	33
Ankle_Inv_Mom_Inv_SS_Change	Pearson Correlation	.012	.138	-.065
	Sig. (2-tailed)	.946	.444	.718
	N	33	33	33
Knee_Flex_Mom_Inv_SS_Change	Pearson Correlation	.117	.027	-.135
	Sig. (2-tailed)	.517	.880	.452
	N	33	33	33
Knee_Abd_Mom_Inv_SS_Change	Pearson Correlation	-.010	-.010	.011
	Sig. (2-tailed)	.954	.956	.954
	N	33	33	33
Knee_Rot_Mom_Inv_SS_Change	Pearson Correlation	.122	.133	.015
	Sig. (2-tailed)	.497	.461	.936
	N	33	33	33
Hip_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.174	-.063	-.019
	Sig. (2-tailed)	.334	.728	.915
	N	33	33	33
Hip_Abd_Mom_Inv_SS_Change	Pearson Correlation	-.095	-.221	-.276
	Sig. (2-tailed)	.600	.216	.121
	N	33	33	33
Hip_Rot_Mom_Inv_SS_Change	Pearson Correlation	.349*	.301	.204
	Sig. (2-tailed)	.047	.089	.254
	N	33	33	33

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-11. Bivariate correlations between kinetic changes during running in the involved limb before and after exercise and change in performance on the square hop task in the involved limb before and after exercise.

Correlations

		SqHop_Time_Inv_Change	SqHop_GCT_Inv_Change
Ankle_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.297	-.077
	Sig. (2-tailed)	.093	.668
	N	33	33
Ankle_Inv_Mom_Inv_SS_Change	Pearson Correlation	-.105	-.192
	Sig. (2-tailed)	.560	.284
	N	33	33
Knee_Flex_Mom_Inv_SS_Change	Pearson Correlation	.144	.029
	Sig. (2-tailed)	.425	.873
	N	33	33
Knee_Abd_Mom_Inv_SS_Change	Pearson Correlation	.245	.144
	Sig. (2-tailed)	.169	.424
	N	33	33
Knee_Rot_Mom_Inv_SS_Change	Pearson Correlation	.190	.046
	Sig. (2-tailed)	.290	.798
	N	33	33
Hip_Flex_Mom_Inv_SS_Change	Pearson Correlation	-.083	.022
	Sig. (2-tailed)	.645	.904
	N	33	33
Hip_Abd_Mom_Inv_SS_Change	Pearson Correlation	.076	.147
	Sig. (2-tailed)	.674	.413
	N	33	33
Hip_Rot_Mom_Inv_SS_Change	Pearson Correlation	-.292	-.438*
	Sig. (2-tailed)	.100	.011
	N	33	33

*. Correlation is significant at the 0.05 level (2-tailed).

Table D-12. Bivariate correlations between kinematic changes during running in the involved limb before and after exercise and change in performance on the square hop task in the involved limb before and after exercise.

Correlations

		SqHop_Time_Inv_Change	SqHop_GCT_Inv_Change
Knee_Flex_Inv_SS_Change	Pearson Correlation	.161	.108
	Sig. (2-tailed)	.370	.549
	N	33	33
Knee_Abd_Inv_SS_Change	Pearson Correlation	.068	-.005
	Sig. (2-tailed)	.705	.979
	N	33	33
Knee_Rot_Inv_SS_Change	Pearson Correlation	-.108	-.240
	Sig. (2-tailed)	.548	.179
	N	33	33
Hip_Flex_Inv_SS_Change	Pearson Correlation	.363*	.471**
	Sig. (2-tailed)	.038	.006
	N	33	33
Hip_Abd_Inv_SS_Change	Pearson Correlation	-.009	.157
	Sig. (2-tailed)	.962	.383
	N	33	33
Hip_Rot_Inv_SS_Change	Pearson Correlation	-.016	-.055
	Sig. (2-tailed)	.929	.759
	N	33	33
Trunk_Flex_Inv_SS_Change	Pearson Correlation	-.070	-.036
	Sig. (2-tailed)	.700	.841
	N	33	33
Lat_Trunk_Flex_Inv_SS_Change	Pearson Correlation	-.158	.042
	Sig. (2-tailed)	.380	.815
	N	33	33
Trunk_Rot_Inv_SS_Change	Pearson Correlation	-.187	-.293
	Sig. (2-tailed)	.296	.098
	N	33	33
vGRF_Inv_SS_Change	Pearson Correlation	.053	-.010
	Sig. (2-tailed)	.769	.958
	N	33	33

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

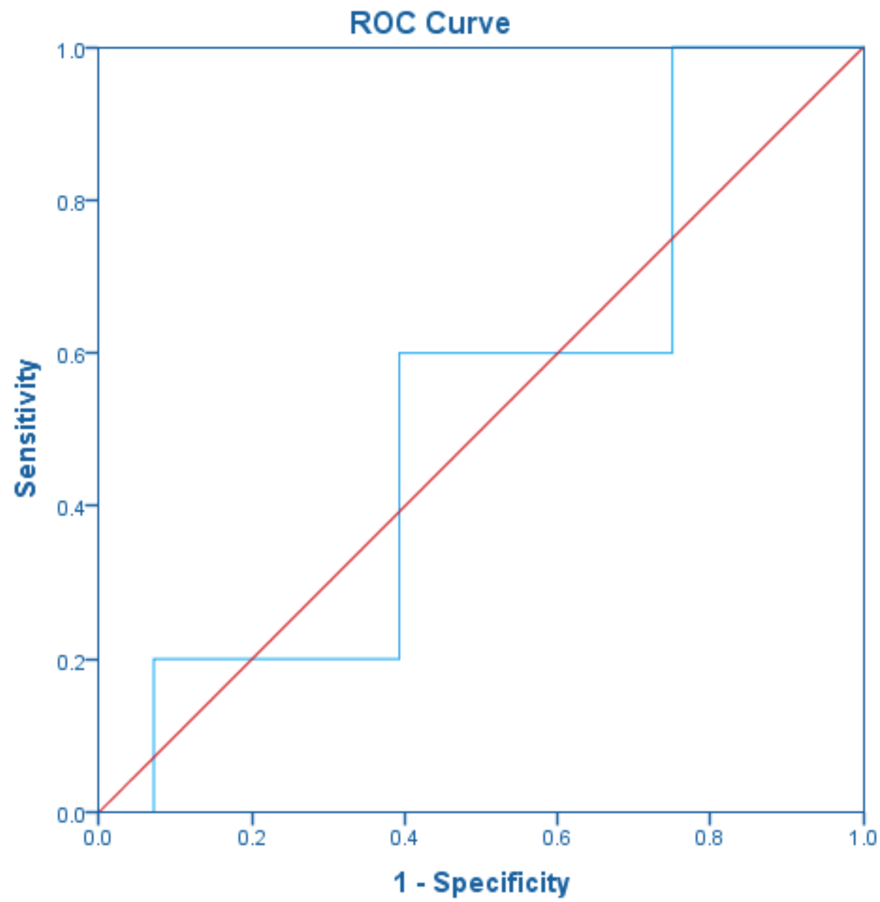


Figure D-18. The ROC curve for symmetry of time on the modified square hop test and side-to-side differences in knee abduction. The area under the curve was 0.529 with p = 0.841.

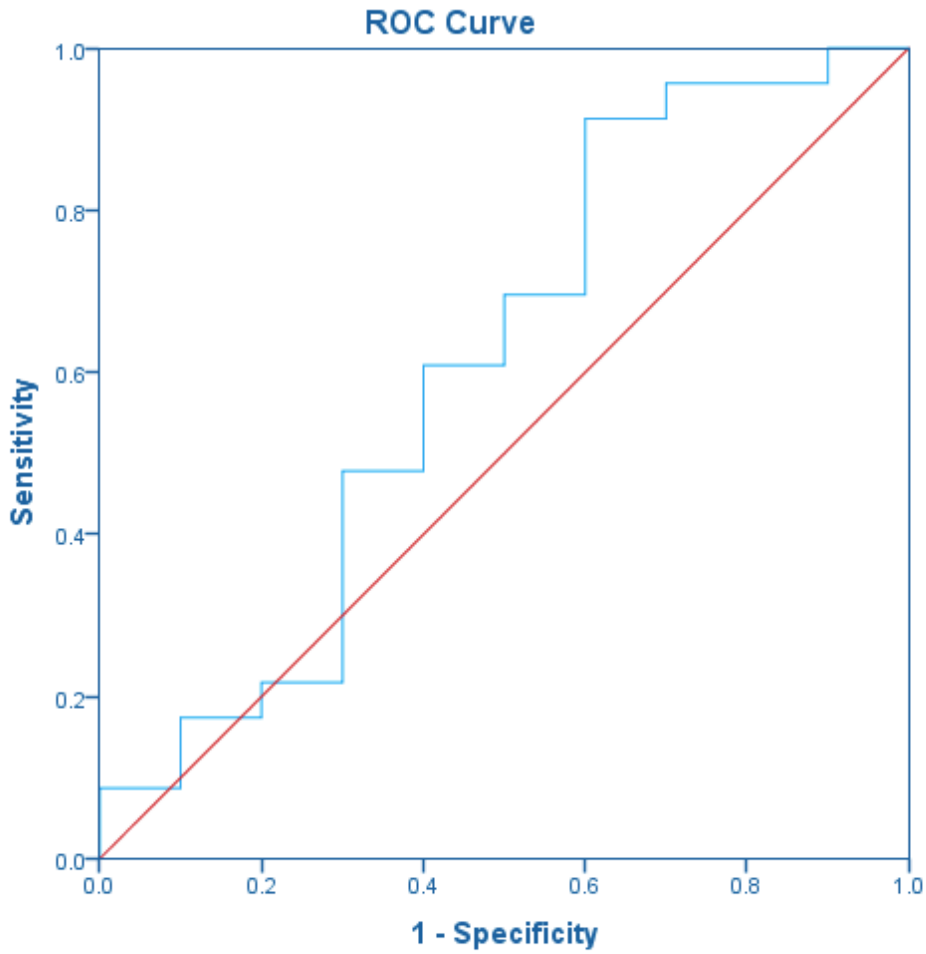


Figure D-19. The ROC curve for knee extension peak torque symmetry and side-to-side differences in hip flexion. The area under the curve was 0.609 with p = 0.327.

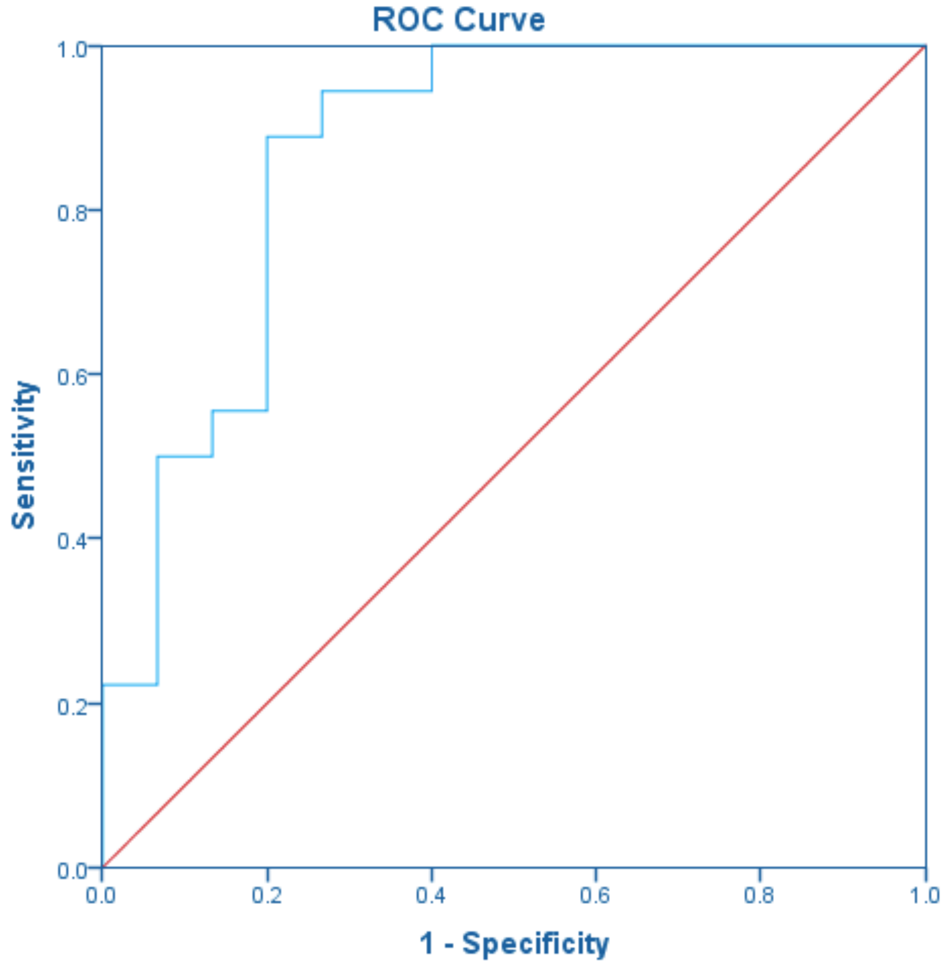


Figure D-20. The ROC curve for knee extension peak torque symmetry and side-to-side differences in vertical ground reaction forces. The area under the curve was 0.870 with $p<0.0001$.

Appendix E

Recommendations for Future Research

1. Do patients with ACLR preserve gait mechanics when exposed to repeated bouts of fatiguing exercise?

2. Can fatigue-related biomechanical adaptations predict lower extremity re-injury risk in active individuals with history of ACLR?

3. What are non-environmental factors that contribute to musculoskeletal injury risk based on fitness levels (e.g. sex, muscle fiber type, cardiovascular fitness)?

4. How do individuals with lower fitness (non-recreationally active) adapt to fatiguing exercise after ACLR?

5. What specific fatigue-related adaptation is most related to injury risk based on fitness level in individuals with history of knee injury?

6. What specific fatigue-related adaptation is more related to re-injury risk based on fitness level in individuals with history of ACLR?

7. Does decision-making or dual-tasking during exercise alter biomechanical adaptations in healthy or ACLR individuals?

8. How does endocrine function change after ACLR and how does it fluctuate after in response to prolonged and fatiguing exercise?

9. Does menstrual cycle affect fatigue-related biomechanical adaptations in females after ACLR?

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