LOWER EXTREMITY FUNCTION IN INDIVIDUALS WITH MEDIAL KNEE DISPLACEMENT

A Dissertation

Presented to

The Faculty of the Curry School of Education

University of Virginia

In Partial Fulfillment

Of the Requirements for the Degree

Doctor of Philosophy

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by

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May, 2017

ABSTRACT

Poor alignment of the lower extremity during functional activities has been shown to increase the likelihood of sustaining a noncontact knee injury. While field-based movement screenings are frequently utilized to identify "high risk" individuals based off of frontal plane movement at the knee, these evaluations have primarily been bilateral. Corresponding with the dynamic unilateral tasks that often occur in athletics, clinicians have recently incorporated the single leg squat (SLS) to screen for dysfunctional movement through the observation of medial knee displacement (MKD). This screening has not been validated, and individuals with and without MKD have not been evaluated to determine whether specific movement strategies exist within each group. Injury prevention programs are often implemented in athletic populations with the goal of reducing noncontact knee injury risk. The programs that have shown the greatest success have all incorporated some form of feedback into their design. While positive changes have been observed when feedback is implemented during dynamic tasks, similar results have not been observed during traditional lower extremity exercises that are slow and repetitive. Therefore, the purpose of this study was compare the visual SLS test for MKD to the knee valgus angle measured on 3DMA (Manuscript 1) and to then compare SLS movement patterns between individuals with and without MKD (Manuscript 2). We subsequently evaluated the effect of a one-session visual feedback intervention focused on correcting frontal plane knee kinematics, in individuals with MKD (Manuscript 3).

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APPROVAL OF THE DISSERTATION

This dissertation, "Lower Extremity Function in Individuals with Medial Knee Displacement", 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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ACKNOWLEDGEMENTS

I would like to acknowledge and thank my dissertation committee, Dr. Sue Saliba, Dr. Jay Hertel, Dr. Joe Hart, and Dr. Shawn Russell, for their guidance and support throughout this research study, and over the past four years. In addition, I would like to thank Neal Glaviano, and Andrea Baellow for their assistance with data collection, and Xue Feng, Ilya Gurin, and Nicholas Vann for their help in software development. Funding for this project was made possible by Accelerated Care Plus, the Curry School of Education, and the Mid-Atlantic Athletic Trainers' Association.

Thank you to Colby Mangum and Lindsay Slater for your perspective, friendship, and support during our time together in this program. To my family, thank you for a lifetime of encouragement in the pursuit of my academic and professional dreams.

Most importantly, to my husband, Kyle – thank you for being my rock during this entire process (the ups, downs, and everywhere in between), and for believing in me through it all. This certainly would not have been possible without your unwavering love and support.

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ABSTRACT

Background: A variety of movement assessments have been utilized in an attempt to identify risk factors for knee injury. Increased knee valgus angle during landing has been recognized as a significant predictor of both anterior cruciate ligament injury and patellofemoral pain, but typically requires 3-dimensional motion analysis (3DMA). Visually observing medial knee displacement (MKD) during functional tasks has been proposed as a low-cost alternative to identify this risk factor. The purpose of this study was to compare the visual single leg squat (SLS) test for MKD to the knee valgus angle measured on 3DMA.

Methods: Thirty-eight recreationally active adults (31F, 7M) volunteered to participate in this study. Participants completed five SLS repetitions and were visually categorized as MKD (if the patella crossed medial to the first ray) or not. Five additional SLS repetitions were measured with 3DMA, utilizing a knee valgus threshold of ≥8° to positively categorize MKD. Assignment as positive or negative MKD was compared the visual test to the 3DMA using a chi-square test, with the level of significance set at $p < 0.05$. Accuracy, sensitivity, specificity and likelihood ratios, and predictive values were calculated for the visual SLS test. An ROC analysis was utilized to determine the optimal cutoff value to compare to the predetermined 8° threshold.

Results: The chi-square test revealed a significant association between both the visual SLS test and 3DMA. The visual SLS test demonstrated an accuracy of 78.95%, sensitivity of 86.67%, and specificity of 73.91%. The positive and negative likelihood ratios was calculated as 3.32 and 0.18, respectively. The positive predictive value was calculated as 68.42% whereas the negative predictive value was calculated as 89.47%.

The ROC analysis produced a knee valgus cutoff point of 7.11°, and an area under the curve of 0.92.

Conclusions: These data indicate that clinicians are effectively able to visually discriminate between “high risk” and “low risk” SLS tasks. The sensitivity of 86.67% coupled with a low negative likelihood ratio, provides strong evidence that those who do not display MKD during the visual test on a SLS do not have the knee valgus risk factor.

Word Count: 345

Key Words: Dynamic Knee Valgus, Functional Assessment, Movement Screening

INTRODUCTION

The knee is one of the most commonly injured lower extremity joints in adolescent athletes, second only to the ankle, with an estimated 2.5 million sports-related injuries occurring each year.[1] Consequently, these injuries result in a relatively high time-loss compared to other injuries.[2] The ability to assess abnormal movement patterns during a functional assessment has become increasingly important when screening for knee injury risk. Rather than observe solely activity-specific movement when determining risk, we must also evaluate functional health based on total movement quality and efficiency. Movement efficiency and functional mobility are qualitative expressions of the kinetic chain and are based on postural stability, strength, endurance and neuromuscular control.[3] One of the most common risk factors for noncontact knee injury is an increase in knee valgus motion during functional tasks.[4,5] It has been suggested that as the knee moves into a valgus position during activity, there is reduced dynamic stability of the joint, and increased potential for injury.[6,7] Dynamic knee valgus (DKV), excessive medial motion of the knee during functional tasks, has been associated with noncontact injury to the anterior cruciate ligament (ACL)[5,8] and medial collateral ligament (MCL),[9] and with patellofemoral pain (PFP).[10-12] In the clinical setting, DKV is often evaluated as the visual observation of medial knee displacement (MKD) by healthcare providers or sports science professionals.

Kinematic evaluation with the use of 3-Dimensional motion analysis (3DMA) is widely regarded as the "gold standard" in the evaluation of biomechanical risk factors. Motion capture systems are reliable during many functional tasks,[13,14] and can accurately determine multi-planar and dimensional kinematics. In particular, they are able to detect

and measure knee valgus angle, the most significant predictor for both acute and overuse knee injuries,[5,8,11] with precision.[15,16] However, 3DMA systems have limited application in the clinical setting due to the high-priced equipment and time consuming set-up, training required for the collection and processing of data, and limited portability. Two-dimensional video analysis has also provided both reliable and valid measurements of frontal and sagittal plane kinematics,[17] although these results are not real-time. Lower extremity movement assessments combat many of the limitations seen with both 3DMA and video analysis, yet are still able to identify dysfunctional movement patterns,[18-20] and therefore risk factors for injury.[5,21]

Functional assessments such as the Functional Movement Screen (FMS)™,[22] Selective Functional Movement Assessment,[22] Star Excursion Balance Test,[23] and the Landing Error Scoring System[19] all have the ability to identify discrepancies in movement quality indicative of injury risk. Previous research has noted that while sports performance professionals value movement assessments, a majority choose to utilize their own systems,[24] which they tend to closely mimic athletic movements and particular training programs or styles.[25] The single leg squat (SLS) is a unilateral, foundational task that has been used to identify faulty lower extremity mechanics, particularly at the knee.[19,26] This task allows clinicians to visually identify kinematic, proprioceptive and neuromuscular control deficits in either a qualitative or quantitative manner, and without the utilization of technology or equipment.

Kennedy et al. asked raters to identify the primary factor limiting SLS performance in their participants, and found intrarater reliability between 0.31 and 0.53, and interrater reliability between 0.26 and 0.37.[27] These suboptimal results suggest that

clinicians were unable to agree on the most significant movement impairment when multiple options were presented to choose from. Similarly, Chmielewski et al. demonstrated that both interrater and intrarater percent agreement were higher when clinicians evaluated overall movement quality of a task versus evaluating individual segment kinematics (Interrater overall quality: 41-82% vs. Interrater segment kinematics: 20-50%; Intrarater overall quality: 56-76% vs. Intrarater segment kinematics: 32-60%), however neither method produced values of agreement that would be considered high.[28] A dichotomous SLS scoring system recently identified medial knee motion to have the strongest association to knee valgus angle measured with 3DMA, and that this risk factor can effectively discriminate between those who have a history of injury, and those who do not.[29] Further evaluation has suggested that frontal plane knee motion is the most important indicator of knee injury risk.[5,11] Although the scoring system correctly predicted if individuals had a previous knee injury, the system has not been evaluated for its utility in the identification of knee injury risk. The SLS has been shown to have acceptable validity when peak knee flexion angle and task speed were standardized,[26,30,31] and when raters assessed video recordings of the task,[32,33] however it is unknown if it is an effective test in the real-time classification of individuals with and without MKD, compared to a knee valgus threshold[5] on 3DMA. Furthermore, the accuracy, sensitivity and specificity, predictive values, and likelihood ratios of this screening have not been previously established, making it difficult for clinicians to integrate this assessment into their practice with an evidence-based approach. Therefore, the purpose of this study was to determine the diagnostic utility of the SLS clinical test for MKD, as compared to the knee valgus angle on 3DMA.

METHODS

Study Design:

This was a descriptive laboratory study. The independent variable was the diagnostic test (visual SLS test and 3DMA). Each participant was categorized using the visual SLS to assign individuals into either positive or negative MKD categories. The test was repeated using 3DMA, assigning individuals into either positive or negative DKV categories, based on an 8º knee valgus threshold. A 2x2 contingency table was developed to evaluate and compare the participant categorization with each test.

Participants:

Volunteers included 38 recreationally active participants (Sex: F=31, M=7; Age: 20.78±2.24 years; Mass: 64.68±12.31 kg; Height:169.77±8.82 cm), recruited as a sample of convenience from the local university community. Participants were excluded if they met any of the following criteria: 1) known neurological condition resulting in a decrease in balance and/or proprioception, 2) infection near the trunk or lower limbs, 3) known pregnancy. Approval was obtained from the University of Virginia's Institutional Review Board (IRB-HSR #17909), and all participants provided written, informed consent prior to enrollment.

Instruments:

Three-dimensional kinematics were collected with a 12-camera motion analysis system (Vicon motion systems, Oxford, UK), and integrated with Motion Monitor software (v. 9, Innovative Sports Training, Inc., Chicago, IL, USA). Thirty-two retroreflective markers (14mm) were configured in eight clusters of four, and secured on semi-rigid thermoplastic plates. Clusters were affixed bilaterally over the dorsum of the

foot, the lateral shank, the lateral thigh, the sacrum, and the thoracic spine with elastic tape. Height and mass were collected, and joint centers were digitized utilizing the stylus. All kinematic data were sampled at 250 Hz.

Procedures:

Participants who met the inclusion & exclusion criteria were enrolled in the study. Procedures are outlined in a STARD flowchart in Figure 1.1. Participants received standardized verbal instructions on the performance of the SLS task, and were permitted up to three practice trials. The task was standardized,[26] and involved participants standing on one limb, with their opposite knee flexed to approximately 90°, and hands folded across their chest. They were instructed to squat down as low as comfortably possible (at least 45°) for two seconds and to return to the starting position for two seconds. A metronome was utilized to ensure consistency in the duration of the task, and a 30-second rest period was provided between each trial. Participants completed five SLS repetitions, which were rated by a certified athletic trainer (ANM) from the anterior view. If three of the five repititions[26,34,35] demonstrated MKD (the center of the patella crossing medial to the first ray[34,36,37]), the individual was allocated to the MKD group. If the participant did not demonstrate three of five SLS repetitions representative of MKD, he or she was allocated to the control group. A trial was considered invalid if the participant lost his or her balance, touched down with the contralateral limb, or did not perform the SLS at the defined rate. Both limbs were evaluated, and the control group was matched to the MKD group based on limb.

The participant was subsequently set-up for 3DMA. A 5-second bipedal quiet standing trial was recorded for kinematic normalization. Participants completed three

trials of the same SLS procedure as they did during the clinical test, with the same verbal instructions.

Data Processing:

Knee valgus joint kinematic data were filtered with a 4th order low-pass Butterworth filter at a cutoff frequency of 14.5 Hz. Joint rotations for the trunk, hip, knee, and ankle were calculated using the Euler rotation method (Y, X', Z''). Data were normalized to knee valgus at quiet standing, and the mean of three trials was used for analysis. Participants were allocated to the MKD group if they demonstrated a peak knee valgus angle ≥8 degrees.[5,34] During data processing, the researcher was blinded to group assignment made during visual observation.

Statistical Analysis:

A 2x2 contingency table was created to compare group assignment based on the visual observation of MKD during the visual SLS test to group assignment based on the knee valgus angle calculated during 3DMA. The contingency table was analyzed using a chi-square test, with the level of significance set at $p < 0.05$. To assess the reliability of the visual SLS test in determining MKD, seven parameters were calculated: accuracy, sensitivity, specificity, positive likelihood ratio (PLR), negative likelihood ratio (NLR), positive predictive value (PPV), and negative predictive value (NPV). The accuracy is the percentage of participants in whom the visual diagnosis is correct, and is determined using the equation: $\frac{true\ positives+true\ negatives}{true\ positives+true\ negatives+false\ positives+false\ negatives} \times 100$. Sensitivity is the ability of a test to detect an abnormality, and is calculated as follows: $\frac{true\ positives}{true\ positives+false\ negatives} \times 100$. Specificity is an assessment of the accuracy of a test result such that the more specific a test, the fewer false positive results, and is determined

using the equation: $\frac{true\ negatives}{true\ negatives+false\ positives} \times 100$. The PLR indicates how much the odds of having a condition increase when the test is positive, and is calculated as follows: $\frac{sensitivity}{(1-specificity)} \times 100$. The NLR indicates how much the odds of having a condition decrease when the test is negative, and is determined using the equation: $\frac{(1-sensitivity)}{specificity} \times 100$. Tests with PLR ≥ 10 or NLR ≤ 0.1 will provide "strong" and nearly conclusive shift in post-test probability. A PLR between 5 and 9.99 and NLR between 0.11 and 0.2 result in "moderate" shifts in post-test probability.[38] The PPV represents the probability of having the condition when the test is positive, and is calculated as: $\frac{true\ positives}{true\ positives+false\ positives} \times 100$. The NPV represents the probability of not having the condition when the test is negative, and is determined using the equation: $\frac{true\ nevatives}{true\ negatives+false\ negatives} \times 100$.

A receiver operating characteristic (ROC) curve was used to find the optimal cutoff point for knee valgus angle within the participant sample in comparison to the reference standard (MKD status). This cutoff value was then compared to the pre-determined knee valgus threshold of 8°. Additionally, an area-under-the-curve (AUC) analysis was conducted to evaluate predictive ability. An AUC of 1.0 indicates perfect accuracy in the determining MKD status, and a value less than or equal to 0.50 indicates poor predictive accuracy. All data were analyzed with SPSS statistical software (v. 24.0, SPSS, Inc., Chicago, IL, USA).

RESULTS

The chi-square test revealed a statistically significant relationship between the group assignment based on visual observation of MKD and group assignment based on a

knee valgus angle threshold of 8º in 3DMA ($\chi^2 = 13.33, p < 0.001$). The total number of true positives, true negatives, false positives and false negatives for the visual SLS test are listed in Table 1.1. The accuracy of the visual test was 78.95%, with an associated sensitivity of 86.67% and specificity of 73.91%. The PLR was calculated as 3.32, and NLR as 0.18. The PPV was calculated as 68.42%, and NPV as 89.47%. The ROC curve produced a cutoff value of 7.11°, and an area under the curve of 0.917 (Figure 1.2).

DISCUSSION

The present study was conducted to examine the diagnostic utility of the SLS test for knee valgus compared to the gold standard 3DMA. These data indicate, with moderate to high sensitivity and specificity, that clinicians are effectively able to visually discriminate between those who have this risk factor and those who do not. The sensitivity of 86.67% coupled with a low NLR, provides strong evidence that those who do not display MKD during the visual test are unlikely to have the DKV risk factor. While predictive values are highly dependent on the prevalence of the condition in the population of interest, Ugalde et al. reported a rate of abnormal posture during the SLS in 51% of the athletes evaluated during their study,[26] which is almost equivalent to the rate of 50% in the present study. In addition, the ROC curve produced a cutoff point of 7.11° of knee valgus angle on 3DMA (Figure 1.2). While the parameters calculated with the 7.11° threshold showed increased diagnostic accuracy (Tables 1.2-1.3), the parameters calculated based off of the pre-established threshold of 8° were still adequate for differentiating between groups. In addition, this threshold was chosen based off of its ability to predict future injury during a drop vertical jump task. The encouraging results

found in the present study during a lower intensity SLS, speaks to the utility of this threshold across multiple functional tasks.

Much of the previous literature evaluating the quality of knee position during the SLS has utilized 2-dimensional video analysis.[39-41] Although these assessments are more efficient than 3DMA, instrumenting with video cameras still requires set-up and processing to acquire the data of interest. In a clinical setting, feedback aimed at correcting aberrant movement during training and rehabilitation is based on visual observation. While visual assessments do not require any equipment and can be implemented in almost any environment, those that utilize more than two categories in the assessment of movement quality[28,42] or ask raters to estimate range of motion values[42,43] have shown inadequate reliability and agreement.

In contrast to our findings, DiMattia et al. found higher specificity (58-78%) than sensitivity (46-54%) when visually evaluating the SLS for a knee valgus angle that appeared to be > 10°.[42] In addition to observing knee valgus, the raters in this study were asked to visually evaluate for hip adduction angle, and knee flexion angle. Raters in a study by Ekegren et al. were asked to evaluate overall movement quality as "high risk" or "low risk" during a drop vertical jump, and did so with moderate specificity (60-72%) and sensitivity (67-87%).[18] The similarity in specificity between these two studies suggest that neither a global rating of movement quality[18] nor an evaluation of multiple lower extremity segments during the same task[42] offers a greater ability of ruling in the DKV condition. However, the increased sensitivity seen in the study by Ekegren et al.[18] provides evidence in support of a dichotomous rating of risk. Both assessment styles ask raters to potentially observe more than they may be capable of doing in real-time, which

may ultimately influence the diagnostic accuracy of the test. As evidenced by both the present study and previous literature,[41] visual assessments of the SLS which focus solely on one risk factor and utilize a dichotomous rating, may be better suited as a screening test.

The goal of a screening test in medicine is to reduce the morbidity or mortality of the group being screened for a particular condition.[44] If a diagnostic test is highly sensitive and the test result is negative, the clinician would have confidence that the individual does not have the condition. Based on these results, individuals with a positive SLS test would benefit from further testing with a highly specific test to formally confirm the presence of the knee valgus risk factor. In the sports medicine setting, impaired motor control has been implicated as both a risk factor for[5,45,46] and the result of[47-49] an orthopedic injury, resulting in risk for primary and secondary injury. The ability for clinicians to confidently identify individuals do not exhibit this risk factor would reduce the time and cost of unnecessary further testing. Additionally, interventions such as neuromuscular training programs and corrective exercise to modulate this risk factor can be focused on those who would benefit the most.

This study was not without limitations. While the SLS was chosen due to its foundational nature, we only evaluated one functional task. Differences in the ability to clinically observe MKD may be present with the analysis of other tasks that are more dynamic, or are completed in a bilateral versus unilateral stance. In addition, the visual SLS test and 3DMA were performed separately, albeit in the same testing session. While this could have potentially affected our results, excellent inter- (ICC=1.00, 95% CI: 0.99 to 1.00) and intra-session (ICC=0.92, 95% CI: 0.80 to 0.97) reliability has been reported

for the measurement of knee valgus,[13] and the participants in both groups demonstrated low inter-trial variability. The ability of the SLS to predict future injury was not assessed in this study, and should be analyzed in the future to aid in the clinical utility of this movement assessment.

CONCLUSIONS

The visual SLS test is an adequate screening assessment for MKD, a surrogate for excessive knee valgus angle measured in 3DMA. The ability to visually identify a kinematic risk factor for lower extremity injury may allow sports medicine professionals to intervene more effectively with corrective exercise, and promote athlete education regarding sport-specific, at-risk positions. Based on the results of this study, the SLS test would be appropriate for large, field-based screenings to target individuals at higher risk with intervention programs.

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Table 1-1. Comparison Between Group Assignment Based on the Visual SLS Test and a Knee Valgus Angle Threshold of 8°on 3DMA

	3DMA (+)	3DMA (-)	Total
Visual SLS Test (+)	13 *(True Positive)*	6 *(False Positive)*	19
Visual SLS Test (-)	2 *(False Negative)*	17 *(True Negative)*	19
Total	15	23	

Table 1-2. Comparison Between Group Assignment Based on the Visual SLS Test and a Knee Valgus Angle Threshold of 7.11°on 3DMA

	3DMA (+)	3DMA (-)	Total
Visual SLS Test (+)	17 *(True Positive)*	2 *(False Positive)*	19
Visual SLS Test (-)	1 *(False Negative)*	18 *(True Negative)*	19
Total	19	20	

Table 1-3. Visual SLS Test Diagnostic Parameters When Compared to a Knee Valgus Threshold of 8° and 7.11°on 3DMA

Parameter	Estimate Based on 8° Threshold	Estimate Based on 7.11° Threshold
Accuracy	78.95%	92.11%
Sensitivity	86.67%	94.44%
Specificity	73.91%	90.00%
Positive Likelihood Ratio	3.32	9.44
Negative Likelihood Ratio	0.18	0.06
Positive Predictive Value	68.42%	89.47%
Negative Predictive Value	89.47%	94.74%

Figure 1-1. STARD Flowchart

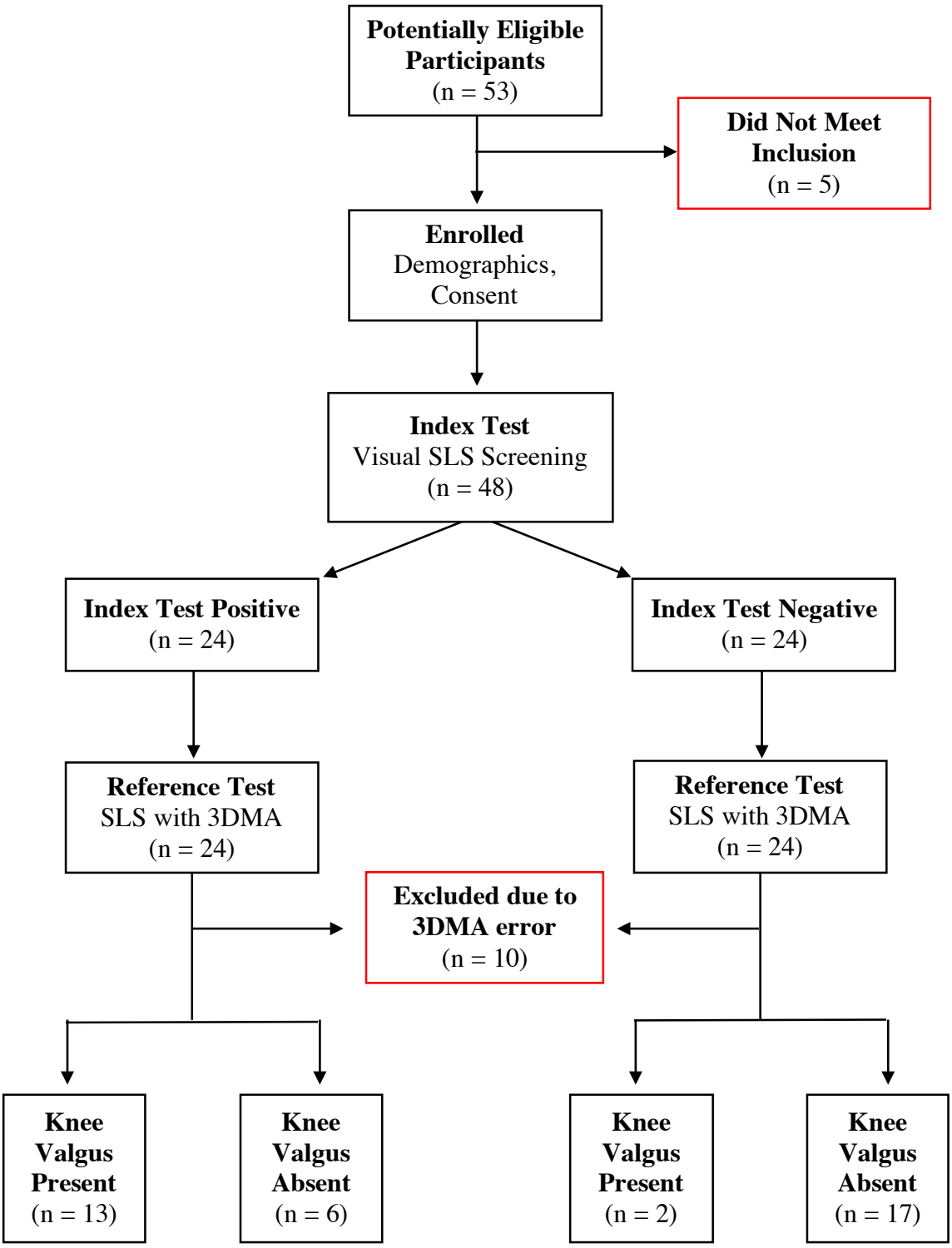
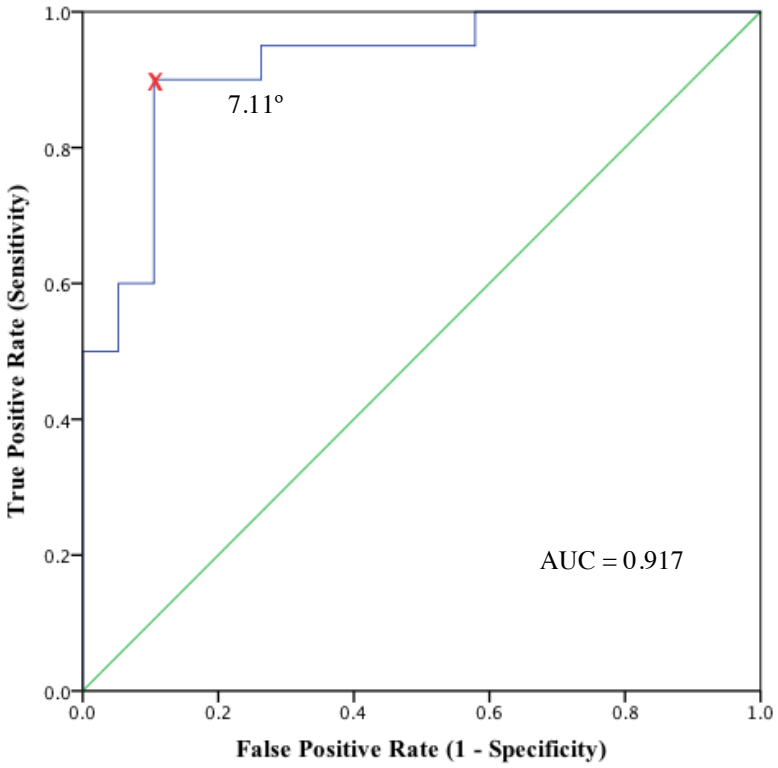


Figure 1-2 Receiver Operating Characteristic Curve for Predicting Individuals with MKD Based on Knee Valgus Angle



Blue line: Knee Valgus Angle in 3DMA
Green line: Reference
Red X: Cutoff point

SECTION II: MANUSCRIPT II

SINGLE LEG SQUAT BIOMECHANICS IN INDIVIDUALS PRESENTING WITH MEDIAL KNEE DISPLACEMENT

ABSTRACT

Background: Individuals presenting with medial knee displacement (MKD) often exhibit alterations in joint kinematics, muscle activity, and strength distal and proximal to the knee joint. These characteristics may contribute to the resultant knee valgus, and increase risk for lower extremity injury. There are few studies that have investigated lower extremity joint kinematics, muscle activity, and hip strength between those who present with MKD on a single leg squat (SLS), and those who do not.

Methods: Thirty-eight recreationally active adults (31F, 7M) volunteered to participate in this study. Participants completed 3 SLS trials, during which triplanar kinematics at the trunk, hip, knee and ankle, and muscle activation of the ipsilateral paraspinal, gluteus maximus, gluteus medius, biceps femoris, adductor, vastus lateralis, vastus medialis obliquus, and medial gastrocnemius were collected. In addition, isometric strength of hip extension, hip abduction, and hip adduction were measured. Time series curve analyses were constructed for normalized lower extremity kinematics, and sEMG activity across the entire SLS task. Three-dimensional kinematics, sEMG normalized peak amplitudes, and isometric hip strength were compared between groups using independent samples t-tests. Muscle co-activation ratios were calculated for the normalized gluteus medius/gluteus maximus and hip adductor muscle activation amplitudes, and isometric hip strength ratios were calculated for normalized hip abduction/extension and adduction. The level of significance was set at $p < 0.05$ *a priori*.

Results: The MKD group exhibited an average of 7.74º more knee valgus throughout a majority of the SLS, 4.68º more ankle internal rotation during the descent and start of the ascent, and greater hip internal rotation during the first 25% of the task (3.58º) and last

17% of the task (3.85º). Additionally, they displayed increased adductor activation and decreased biceps femoris activation throughout a majority of the SLS, along with a short period of decreased vastus lateralis activity from 8-15%, and decreased gluteal activity in both the beginning and end of the task. Those in the MKD group also displayed significantly lower mean GMed:ADD ratio compared to the control group, indicating greater hip adductor sEMG activation compared with gluteus medius sEMG activation. No significant differences were seen in hip strength measures between groups. Additionally, there was no difference in the HipAbd:HipAdd isometric strength ratio between groups.

Conclusions: Individuals with MKD presented biomechanical alterations at the ankle, knee and hip during the SLS. Multi-joint alterations can be observed during a low intensity, unilateral task, and these findings contribute to the body of literature regarding lower extremity movement patterns.

Word Count: 405

Key Words: Dynamic Knee Valgus, Functional Task, Movement Pattern

INTRODUCTION

Poor alignment of the lower extremity during functional activities has been shown to increase the likelihood of sustaining a noncontact knee injury.[1-3] In particular, increased frontal plane motion at the knee has been discouraged during landing and plyometric tasks,[1,4] as it places increased stress on the mechanical restraints and stabilizing structures.[5] The dynamic knee valgus (DKV) movement pattern is defined as a strategy utilized during functional tasks that results in excessive knee valgus motion.[4] This movement pattern has been deemed a composite motion with multi-planar ankle, knee, hip and trunk contributions, and is visually observed as medial knee displacement (MKD) on visual screenings. Researchers have associated excessive motion at the knee during landing with ACL injury risk, and have utilized the strategy to prospectively identify those at risk for future injury.[4,6-8] Primary associations have been made between increases in lateral trunk flexion, hip internal rotation, knee valgus, ankle eversion, and a decrease in ankle dorsiflexion, during functional tasks. In order to effectively address neuromuscular issues pertinent to knee injury, quantification of the involved movements is necessary.

Motor recruitment strategies[1,3,9] and muscular strength imbalances[1,3,10,11] have been reported as contributing factors to the MKD movement during functional tasks. Imbalances in neuromuscular activation has been identified between the quadriceps and hamstrings,[1,3] which has been hypothesized to lead to increased knee valgus. Another theory identified weak or underactive hamstrings,[4] which leads to a decrease in quadriceps contribution, and thus an altered relationship. It has been proposed that as a result of this decreased co-contraction, there is an increase in excessive frontal plane

movement at the knee.[4] Recently, focus has been placed on evaluating the relationship between hip abductor strength and knee valgus motion. The MKD strategy has traditionally been associated with deficits in strength, muscular imbalances and poor neuromuscular control of the hip and trunk,[9,10] however minimal correlation has been found between the strategy and the aforementioned deficits.[10,11]

Prior to implementing movement correction or injury prevention programs, effective screening methods for established risk factors should be utilized to identify aberrant movements.[12,13] Both qualitative and quantitative visual assessments of individuals displaying MKD have been described during squatting and landing. The drop vertical jump,[4,8] tuck jump,[14,15] and overhead squat,[16,17] have demonstrated validity and reliability as screening tests, however they are all bilateral in nature. Similarly, the single leg squat (SLS) has recently been validated as a method to identify individuals presenting with MKD with both a dichotomous scoring system,[18]and with qualitative visual observation.[19,20] Previous studies evaluating the SLS[10,11,21] have excluded individuals with a history of lower extremity injury, yet frontal plane deficits exist at the hip and knee in athletes up to 4 years following ACL reconstruction,[22] and it has been suggested that lower extremity injury is the greatest risk factor for future injury. These findings suggest that further research using the SLS task is warranted to aid in the identification of injury risk factors.

In an effort to correct the MKD, clinicians have focused on improving neuromuscular control, strength, and motor learning, however little research has been conducted utilizing the SLS task. The purpose of this study was to compare the overall comprehensive movement strategy – including lower extremity kinematics, muscular

activation, and hip isometric muscle strength – during a SLS, in those presenting with and without MKD.

METHODS

Study Design:

This was a descriptive laboratory study to compare lower extremity kinematics, muscle activity, and hip strength during a SLS, between individuals with and without clinically observed MKD. The independent variable was group (MKD and control), and the dependent variables were lower extremity kinematics and surface electromyography (sEMG) activity throughout 100% of the SLS task, and isometric hip strength.

Participants:

Thirty-eight recreationally active (self-reported, 30 minutes/day for at least 3 days/week) participants between the ages of 15 and 40 years were recruited from the local university community setting, and volunteered to participate. Each participant was assigned to either the "MKD" group or the "control" group based on SLS screening performance, and there were no significant differences in demographics observed between the control and MKD groups (Table 2-1).

Exclusion criteria included any known neurological condition resulting in a decrease in balance and/or proprioception, infection near the trunk or lower limbs, or known pregnancy. For the purposes of this study, we did not exclude history of lower extremity injury, as long as the participant was able to complete the SLS task. This study was approved by the University of Virginia's Institutional Review Board (IRB-HSR #17909), and all participants provided written, informed consent prior to enrollment.

Instruments:

Three-dimensional joint kinematics of the trunk, hip, knee, ankle were measured with a 12-camera motion analysis system (Vicon Motion Systems, Oxford, UK), and Motion Monitor software (v. 9, Innovative Sports Training, Inc., Chicago, IL, USA) at a sampling rate of 250 Hz. Thirty-two retroreflective markers (14mm) were configured in eight clusters of four, and secured on semi-rigid thermoplastic plates. Clusters were affixed bilaterally over the dorsum of the foot, the lateral shank, the lateral thigh, the sacrum, and the thoracic spine with elastic tape. Height and mass were collected, and joint centers were digitized utilizing the stylus.

sEMG was collected using the Trigno wireless surface EMG system (Delsys, Inc., Boston, MA, USA) and integrated with Motion Monitor software (Innovative Sports Training, Inc., Chicago, IL, USA). Parallel bar electrode sensors ($37mm \times 26mm \times 15mm$, DE 2.1 differential) were utilized to collect muscle activation at 2,000 Hz. Each bar was $1mm \times 1cm$, and the inter-electrode distance was 1cm. Input impedance was $> 10^{15}\Omega/0.2pF$ with a signal to noise ratio of $1.2u$.

Isometric strength for hip abduction, and hip adduction was collected using a handheld dynamometer (HHD) (Accelerated Care Plus Corporation, Reno, NV, USA). For hip abduction, the HHD was placed on the lateral surface of the upper leg, 5cm proximal to the knee joint line. For hip adduction, the HHD was placed on the medial surface of the upper leg, 5cm proximal to the knee joint line.

Procedures:

Individuals who met the inclusion & exclusion criteria were enrolled into the study. Procedures are outlined in a CONSORT flow chart in Figure 2-1. Participants were allowed to warm-up for 5 minutes, and subsequently completed a visual SLS screening

test. Participants stood on one limb with the opposite knee flexed to approximately 90° and hands folded across their chest. They were instructed to squat down as low as comfortably possible for two seconds and to return to the starting position for two seconds. A metronome was utilized to ensure consistency in the duration of the task, and a 30-second rest period was provided between each trial. Both limbs were screened with the SLS test. Participants were placed into the MKD group if the midpoint of the patella crossed medial to the 1st ray in at least 3 of 5 SLS trials, and into the control group if the knee remained in line with the hip and ankle joints in at least 3 of 5 SLS trials.[23] If a participant presented with MKD on both sides, the limb of interest was randomly selected. Participants were not informed of which group they were placed in an effort to avoid potential influence on their performance of future SLS trials during the testing session. Limb of interest for control participants was selected to match the MKD participants: non-dominant vs. dominant leg.

Following the SLS screening, sEMG sensors were placed over the ipsilateral paraspinal, gluteus maximus (GMax), gluteus medius (GMed), and adductor longus (ADD), vastus lateralis (VL), vastus medialis obliquus (VMO), biceps femoris (BF), adductor longus (ADD), and medial gastrocnemius (MGas).[24] Electrode sites were identified, shaved, abraded and cleaned with isopropyl alcohol in an effort to reduce impedance, and placement was confirmed during both quiet standing, and MVIC. Three 5-second MVIC trials were conducted to assess hip abduction and adduction isometric strength.[25] If it was determined that an MVIC trial exceeded 10% variability, an additional trial was collected. The average force (N) of each MVIC trial was recorded,

and the mean of the 3 trials was calculated and normalized to the participant's body mass (kg).

Participants were subsequently set-up for motion analysis. A bipedal quiet standing trial was recorded for 5-seconds for both sEMG and kinematic normalization. Participants completed 3 trials of the same SLS procedure as they did during the screening portion of the testing session, with the same verbal instructions. A metronome was again utilized to standardize the rate of the task.

Data Processing:

During data processing, the researcher was blinded to group assignment made during visual observation. Kinematic and muscle activity analyses were performed beginning at the initiation of knee flexion through the return to full knee extension during the SLS task. Kinematics and sEMG activation amplitudes were reduced to 101 frames, so that each frame represented 1% of the task.

Kinematics

Kinematic data were filtered with a 4^{th} order low-pass Butterworth filter at a cutoff frequency of 14.5 Hz. Joint rotations for the trunk, hip, knee, and ankle were calculated using the Euler rotation method (Y, X', Z''). Data were normalized to kinematics at quiet standing.

sEMG Amplitudes

Data were filtered using band-pass (10-500 Hz) and notch (50 Hz) filters, and smoothed using a 50-sample moving window root mean square (RMS) algorithm. SLS muscle activity was normalized to quiet standing muscle activity for all 8 muscles.

Statistical Analysis:

Continuous Analysis

Time series curve analyses were constructed for normalized lower extremity kinematics, kinetics, and sEMG activity. Group means and associated 90% confidence intervals were reduced to 101 frames and plotted for the duration of the task, so that each frame represented 1% of the task. The mean of the three trials was used for analysis, and 50% was representative of peak knee flexion, so that 1-50% represented the descending phase and 51-100% represented the ascending phase of the SLS. Areas where the confidence intervals did not overlap for at least three consecutive percentage points between the two groups (MKD and control) were considered statistically significant.

Discrete Analysis

Tri-dimensional kinematic and sEMG peaks were extracted and compared to kinematics and sEMG at quiet standing to calculate total kinematic excursions and normalized sEMG amplitudes. Discrete variables were compared between groups using independent samples t-tests. The level of significance was set at $p < 0.05$ *a priori*. Cohen's d effect sizes and associated 95% confidence intervals were calculated to estimate the magnitude of difference between the two groups. Effect sizes were interpreted as ≥ 0.80 large, $0.50 - 0.79$ moderate, $0.20 - 0.49$ small, and < 0.20 trivial.[26]

Muscle co-activation ratios were calculated for the normalized gluteus medius and hip adductor muscle activation amplitudes by dividing the mean gluteus medius activity during the SLS task by the mean hip adductor activity during the SLS task (GMed:Add). A ratio of 1.0 would indicate complete muscular co-activation. Ratios greater than 1.0

indicate greater activation of the numerator (GMed) as compared to the denominator (Add).

A normalized isometric strength co-activation ratio was calculated by dividing the mean hip abduction strength by the mean hip adduction strength (HipAbd:HipAdd). A ratio of 1.0 would indicate completely balanced strength. A ratio greater than 1.0 would indicate greater strength of the numerator (HipAbd) as compared to the denominator (HipAdd).

All data were analyzed with SPSS statistical software (v. 24.0, SPSS, Inc., Chicago, IL, USA).

RESULTS

Continuous Analysis:

A significant increase in knee valgus was observed for the MKD group during 8-83% (mean difference: 7.74º, 90% CI: 6.45 to 9.03) of the SLS task as compared to the controls (Figure 2-3). There was also a significant increase in ankle internal rotation from 0-63% (mean difference: 4.68º, 90% CI: 3.08 to 6.28), and increase in hip internal rotation from 0-25% (mean difference: 3.58º, 90% CI: 3.05 to 4.10) and 83-100% (3.85º, 90% CI: 3.62 to 4.09) in the MKD group compared to the controls (Figure 2-4). No other kinematic differences were observed between groups (Figures 2-2 to 2-4).

Those in the MKD group displayed an increase in adductor activation during 11-88% (mean difference: 5.11, 90% CI: 3.19 to 7.04) and 92-100% (mean difference: 1.14, 90% CI: 0.94 to 1.35), a decrease in biceps femoris activation during 0-33% (mean difference: -4.93, 90% CI: -5.58 to -4.27), 35-84% (mean difference: -5.47, 90% CI: -5.98 to -4.97), and 91-98% (mean difference: -3.06, 90% CI: -3.24 to -2.88), a decrease

in gluteus maximus activation during 8-33% (mean difference: -1.66, 90% CI: -2.20 to -1.11) and 91-95% (mean difference: -2.65, 90% CI: -2.88 to -2.41), a decrease in gluteus medius activation from 0-4% (mean difference: -2.37, 90% CI: -2.57 to -2.17), 6-20% (mean difference: -2.60, 90% CI: -2.85 to -2.35), 22-26% (mean difference: -2.55, 90% CI: -2.61 to -2.48) and 93-100% (mean difference: -3.56, 90% CI: -4.24 to -2.87), and a decrease in vastus lateralis activation from 8-15% (mean difference: -6.29, 90% CI: -7.23 to -5.36) of the SLS as compared to the control group (Figures 2-5a to 2-5b). No other muscular activation differences were observed between groups.

Discrete Analysis:

The MKD group presented with increased peak knee valgus (mean difference: 7.53º, 95% CI: 3.74 to 11.32, $p < 0.001$), and ankle internal rotation (mean difference: 4.82º, 95% CI: 0.88 to 8.77, $p = 0.017$) compared to the control group. Each of these differences had large clinically meaningful effect sizes (knee valgus: $Cohen's\ d = 1.31$, 95% CI: 0.61 to 2.01; ankle internal rotation: $Cohen's\ d = 0.81$, 95% CI: 0.15 to 1.47). Although the MKD group exhibited a statistically significant increase in peak hip internal rotation (mean difference: 3.69º, 95% CI: -0.88 to 6.49), the CI crossed zero, suggesting no meaningful difference between groups. A trend towards significance was also noted in ankle eversion (mean difference: 2.89º, 95% CI: 0.002 to 1.31, $p = 0.051$), with a moderate effect ($Cohen's\ d = 0.65$, 95% CI: 0.002 to 1.31). There were no other discrete kinematic differences between groups (Table 2-2).

Individuals in the MKD group displayed significantly greater peak normalized adductor activation (mean difference: 12.53, 95% CI: 5.80 – 19.27 $p = 0.001$) and lower peak biceps femoris activation (mean difference: 6.80, 95% CI: 0.48 – 13.12, $p = 0.036$)

as compared to the control group. Both differences resulted in clinically meaningful effects (adductor: $Cohen's\ d = 1.62$, 95% CI: 0.89 – 2.36; biceps femoris: $Cohen's\ d = 0.65$, 95% CI: 0.30 – 1.65) (Table 2-3). The MKD group also displayed a significantly lower mean GMed:ADD ratio compared to the control group, indicating greater hip adductor sEMG activation compared with gluteus medius sEMG activation (Figure 2-6).

No significant differences were seen in hip strength measures between groups (Table 2-4). Additionally, there were no differences in the HipAbd:HipAdd isometric strength ratio between groups, as both displayed greater gluteus medius isometric strength as compared to adductor strength (Figure 2-7).

DISCUSSION

The purpose of this study was to utilize a visual screening to categorize potential risk in individuals based on whether or not they displayed MKD. Biomechanical factors were examined to better understand the overall movement pattern, and to identify modifiable aspects of the strategy. Individuals presenting with MKD exhibited strategies at the ankle, hip and knee during the SLS task. A trend towards significance with a moderate effect size was also noted with the MKD group exhibiting greater peak ankle eversion than the control group. Furthermore, these participants presented with greater hip adductor and less biceps femoris activity at peak and throughout the task, and less gluteal activation during the beginning and end of the task. The co-activation ratio between the adductor and gluteus medius muscles was different between groups, suggesting greater hip adductor contribution in the MKD group.

The dynamic knee valgus movement pattern has been described as a multiplanar motion with frontal plane (lateral trunk flexion, hip adduction, knee valgus, ankle

eversion) transverse plane (hip internal rotation, tibial rotation), and sagittal plane (decreased ankle dorsiflexion) contributions,[4,27-29] however not all of these components were observed during the SLS in this study. The MKD group exhibited greater knee valgus throughout 8-83% of the SLS task, in addition to 7.53º greater peak knee valgus excursion ($Cohen's\ d = 1.31$), compared to the control group. This difference is very similar to previously documented differences in females who went on to sustain an ACL injury (9º) and those who did not (1.4 º),[4] and has been widely recognized as a primary biomechanical risk factors for ACL injury,[4,27] MCL injury,[30,31] and PFP.[32,33] This aberrant movement has been documented in both bilateral[8,32,34] and unilateral[35-37] tasks, suggesting that it is not task specific.

The involvement of kinematic alterations at the foot and ankle towards the proximal MKD movement has been an area of recent attention.[36,38,39] Individuals with decreased ankle dorsiflexion have demonstrated altered proximal strategies, such as increased knee valgus,[36,40] hip adduction[4] and lateral trunk lean,[41] However, increased knee valgus without associated dorsiflexion limitations has also been observed during functional tasks.[23] The presence of MKD in this study did not appear to be indicative of decreased ankle sagittal plane motion, which may provide insight into the movement strategy utilized when there is not a distal restriction. The alternative strategy observed in the MKD group during this study was an increase in ankle internal rotation through the first 63% of the task, as well as at peak excursion (mean difference: 4.82º, $Cohen's\ d = 0.81$) when compared to the controls. It is possible that a difference in foot type existed between groups, contributing to the excessive transverse plane motion at the ankle.

Burns et al. observed that individuals with pes cavus demonstrated significantly less weight-bearing dorsiflexion range of motion as compared to those with normal alignment, and pes planus,[42] and pes planus has been associated with hyperpronation in adults.[43] It is theorized that excessive pronation during weight-bearing tasks results in tibial internal rotation, and compensatory internal rotation at the femur.[44] While we did not directly measure pronation, we did observe transverse plane adaptations at both the ankle and hip which correspond with these hypotheses. Individuals in the MKD group started and remained in a hip internally rotated position during the SLS, with significant differences noted during the first 25% and final 17% of the task when compared to those in the control group. While foot and ankle mobility were not evaluated in the present study, these characteristics have also been shown to be significantly related to the frontal plane projection angle, a 2-dimensional measure of knee valgus,[39] and could potentially play a role in other functional tasks.

Clinically, is hypothesized that an increase in knee valgus during functional tasks is related to a decrease in gluteal strength,[9,45] although, a recent study has shown little correlation between the two.[10] We did not see any deficits in gluteus maximus or gluteus medius strength, or strength ratios with the adductor musculature in the MKD group. However, it was observed that the MKD group exhibited a co-activation ratio between the adductor and gluteus medius musculature that favored the adductors. We also observed decreased gluteal activity during the beginning and end of the task, greater peak adductor activity (mean difference: 12.53, $Cohen's\ d = 1.62$), and an increase in adductor activity throughout a majority of the SLS in the MKD group. This indicates that hyperactivity of the adductors, which is not counteracted by concomitant increases in

activity of the gluteus medius and gluteus maximus, may result in increased knee valgus. These findings are consistent with previous literature evaluating muscle activation in a population with MKD. Padua et al. reported 34% greater adductor muscle activity in individuals with MKD during a double leg squat,[46] and Mauntel et al. observed 34% greater adductor activation during the descent phase of the SLS.[36] While both authors found no associated differences between groups for the activation of the gluteus medius and gluteus maximus muscles, these studies did not report muscular activity throughout the entirety of the task. We have identified an activation pattern that changes depending on the amount of knee flexion. Movement pattern alterations in this subgroup should focus on incorporating both a reduction in adductor activity and an increase in gluteus medius activity in an effort to restore the co-activation ratio.

Significantly less biceps femoris activation in the MKD group was noted during a total of 89% of the SLS, with an associated decrease in peak normalized biceps femoris activity (mean difference: 6.8, $Cohen's\ d = 0.65$). A decrease in hamstring activation without an associated decrease in quadriceps activation would result in an altered Quadriceps:Hamstring co-activation ratio. This imbalance has been well documented as a risk factor for knee injury,[1,47] as it decreases dynamic control, and increases anterior tibial shear forces. Furthermore, this disparity may be exacerbated with more dynamic landing and pivoting tasks.[5,48] While this finding is contrary to other studies who have reported an increase in biceps femoris activity associated with increased knee valgus,[5,48] the increased ankle internal rotation observed in the present study may explain a different movement strategy.

The SLS screening tool has been successful in diagnosing movement distortions, however the resultant dynamic knee valgus risk factor may be composed of an assortment of components. Consequently, clinicians should utilize an impairment-based approach when implementing corrective exercise or rehabilitation programs. Potential solutions to the observed movement pattern alterations include the incorporation of myofascial release,[16] trigger point massage techniques, or biofeedback[49,50] to aid in inhibition and reduce muscle activity, versus traditional methods focused on increasing muscle activity. While we did not see any associated decreases in gluteal activity within this study, exercises to increase the strength of these muscles would be beneficial in adjusting co-activation ratios. Focus placed on the inhibition and lengthening of the tightened/overactive musculature, activation and strengthening of the inhibited/weak musculature, and integration to ensure proper timing during functional tasks would theoretically serve to restore the muscular balance surrounding the hip and knee joints.[51-53] Similar exercise strategies have been successful in correcting both upper and lower crossed syndromes.[51] Moreover, visual biofeedback may provide an opportunity for a global lower extremity intervention.[54,55]

CONCLUSION

Kinematic and muscle activation differences at the ankle, knee, and hip were observed between individuals with and without MKD during a SLS. These findings contribute to the body of literature noting that dynamic knee valgus is a multifactorial movement pattern, and multi-joint alterations are able to be observed during a unilateral low intensity task.

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Table 2-1. MKD and Control Group Participant Demographics

	MKD (n=19)	**Control (n=19)**	**p-value**
Sex	F=16; M=3	F=15; M=4	
Age (yrs)	20.78 (2.44)	20.63 (2.03)	0.844
Height (cm)	167.77 (8.89)	171.75 (8.25)	0.161
Mass (kg)	62.01 (12.39)	67.21 (11.65)	0.191

MKD = Medial Knee Displacement
yrs = years, cm = centimeters, kg = kilogram

Table 2-2. Peak Kinematic Excursions During the SLS in Individuals With and Without Medial Knee Displacement

	Control (Mean ± SD)	MKD (Mean ± SD)	Mean Difference (95% CI)	p-value	Effect Size (95% CI)
Ankle Kinematics (º)					
Ankle Dorsiflexion	26.88 ± 10.80	31.72 ± 9.45	4.85 (-1.84 to 11.51)	0.150	0.48 (-0.17 to 1.12)
Ankle Eversion	7.26 ± 4.75	10.15 ± 4.05	2.89 (0.02 to 5.79)	0.051	0.65 (0.002 to 1.31)
Ankle Internal Rotation*	10.26 ± 4.57	15.08 ± 7.08	4.82 (0.88 to 8.77)	0.017	0.81 (0.15 to 1.47)
Knee Kinematics (º)					
Knee Flexion	77.61 ± 13.55	80.61 ± 12.64	2.99 (-5.63 to 11.61)	0.486	0.23 (-0.41 to 0.87)
Knee Valgus*	3.63 ± 4.75	11.16 ± 6.62	7.53 (3.74 to 11.32)	<0.001	1.31 (0.61 to 2.01)
Knee Internal Rotation	5.05 ± 3.42	5.14 ± 3.62	0.09 (-2.23 to 2.41)	0.938	0.03 (-0.61 to 0.66)
Hip Kinematics (º)					
Hip Flexion	66.79 ± 14.80	60.90 ± 18.03	5.89 (-4.97 to 16.74)	0.279	-0.36 (-1.00 to 0.28)
Hip Adduction	15.70 ± 7.93	16.77 ± 6.22	1.07 (-3.62 to 5.76)	0.646	0.15 (-0.49 to 0.79)
Hip Internal Rotation*	4.13 ± 4.51	7.82 ± 3.99	3.69 (-0.88 to 6.49)	0.011	0.87 (0.20 to 1.53)
Trunk Kinematics (º)					
Trunk Flexion	9.29 ± 4.79	11.11 ± 5.13	1.82 (-1.44 to 5.08)	0.265	0.37 (-0.27 to 1.01)
Trunk Lateral Flexion *(Ipsilateral)*	4.04 ± 5.29	4.13 ± 4.76	0.08 (-3.39 to 3.23)	0.959	0.02 (-0.62 to 0.65)
Trunk Rotation *(Ipsilateral)*	5.28 ± 4.19	3.75 ± 3.80	1.53 (-1.10 to 4.16)	0.245	-0.38 (-1.02 to 0.26)

* = Significant difference between control and MKD groups at $p < 0.05$
A positive effect size indicates a greater kinematic excursion in the MKD group compared to the Control group
MKD = Medial Knee Displacement, SD = Standard Deviation, CI = Confidence Interval

Table 2-3. Normalized Peak sEMG Amplitudes During the SLS in Individuals With and Without Medial Knee Displacement

	Control (Mean ± SD)	MKD (Mean ± SD)	Mean Difference (95% CI)	p-value	Effect Size (95% CI)
Paraspinal	10.99 ± 4.96	14.76 ± 11.28	3.76 (-12.22 to 4.70)	0.185	0.43 (-0.21 to 1.08)
Gluteus Maximus	17.31 ± 8.95	13.31 ± 7.47	3.99 (-3.50 to 11.50)	0.278	-0.54 (-1.18 to 0.11)
Gluteus Medius	20.09 ± 8.97	18.18 ± 7.54	1.91 (-5.64 to 9.45)	0.603	0.08 (-0.56 to 0.71)
Vastus Lateralis	41.92 ± 19.68	38.30 ± 8.24	3.62 (-9.25 to 16.49)	0.581	-0.24 (-0.88 to 0.40)
Vastus Medialis Obliquus	126.27 ± 41.52	126.69 ± 52.47	0.43 (-41.72 to 40.87)	0.983	0.01 (-0.63 to 0.64)
Biceps Femoris*	17.79 ± 7.63	10.99 ± 6.22	6.80 (0.48 to 13.12)	0.036	-0.98 (-1.65 to -0.30)
Adductor Longus*	18.80 ± 9.93	6.27 ± 4.52	12.53 (5.80 to 19.27)	0.001	1.62 (0.89 to 2.36)
Medial Gastrocnemius	14.39 ± 11.34	10.27 ± 6.30	4.12 (-5.71 to 13.94)	0.372	-0.45 (-1.09 to 0.19)

* = Significant difference between control and MKD groups at $p < 0.05$
A positive effect size indicates greater muscular activation in the MKD group compared to the Control group
MKD = Medial Knee Displacement, SD = Standard Deviation, CI = Confidence Interval

Table 2-4. Hip Musculature Strength for the MKD and Control Groups

	Control (Mean ± SD)	MKD (Mean ± SD)	Mean Difference (95% CI)	p-value	Effect Size (95% CI)
Hip Abduction	3.26 ± 0.90	3.18 ± 0.92	-0.08 (-0.70 to 0.54)	0.808	-0.09 (-0.74 to 0.57)
Hip Adduction	4.96 ± 1.58	5.02 ± 1.42	0.06 (-0.96 to 1.08)	0.905	0.04 (-0.61 to 0.69)

A positive effect size indicates greater muscular activation in the MKD group compared to the Control group
MKD = Medial Knee Displacement, SD = Standard Deviation, CI = Confidence Interval

Figure 2-1. CONSORT Flowchart

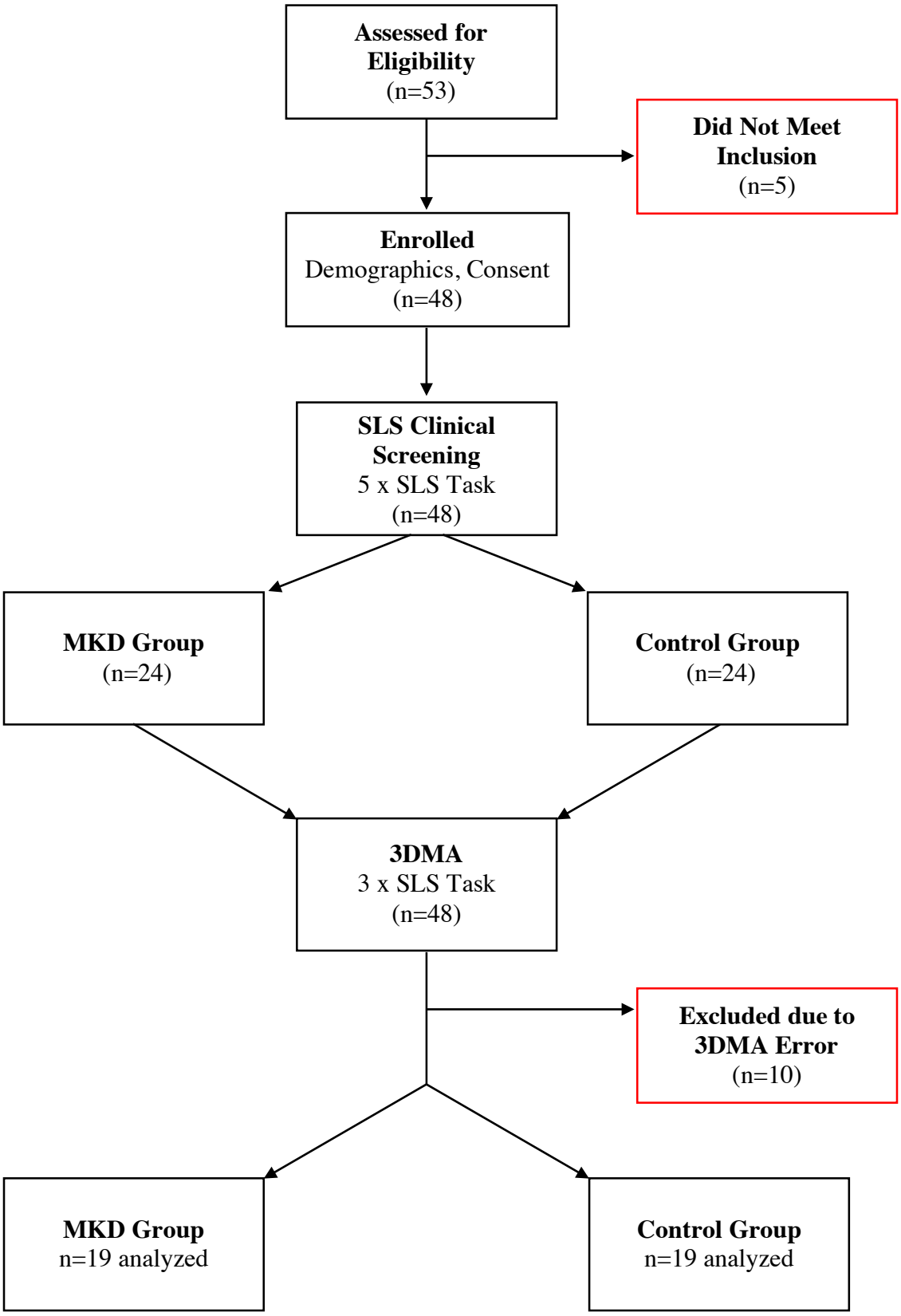


Figure 2-2. Time Series Curve Analysis for Sagittal Plane Kinematics During the SLS

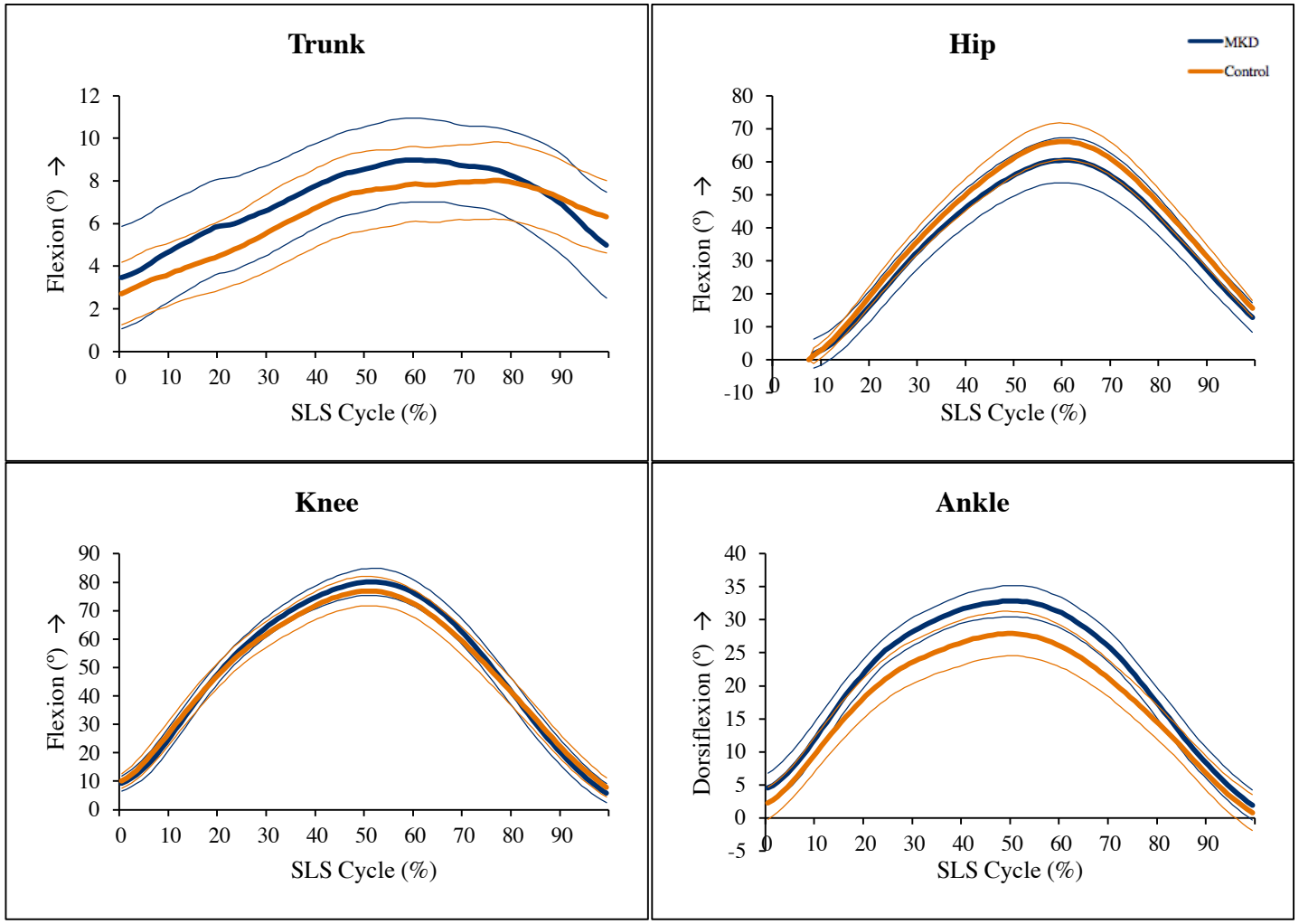


Figure 2-3. Time Series Curve Analysis for Frontal Plane Kinematics During the SLS

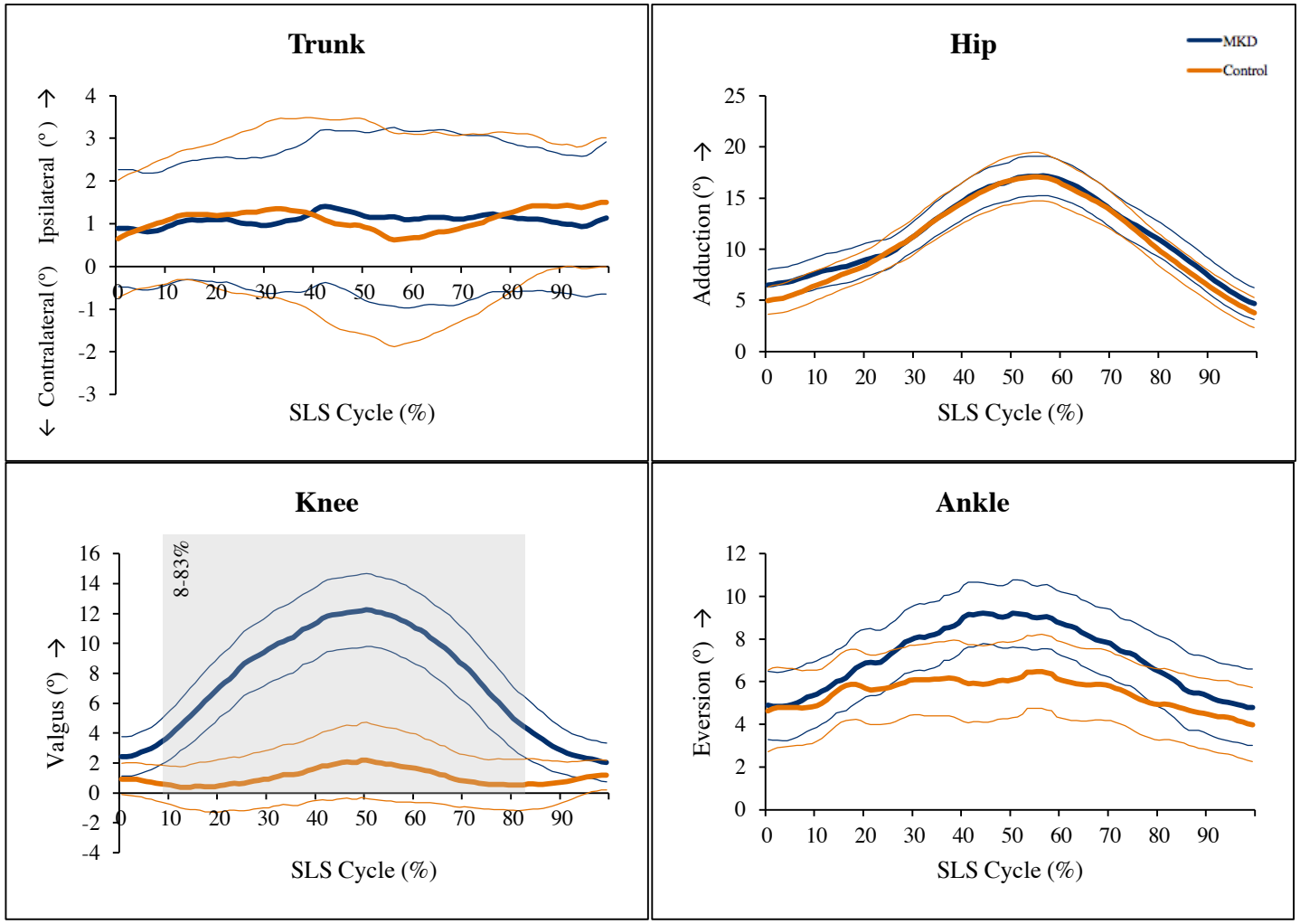


Figure 2-4. Time Series Curve Analysis for Transverse Plane Kinematics During the SLS

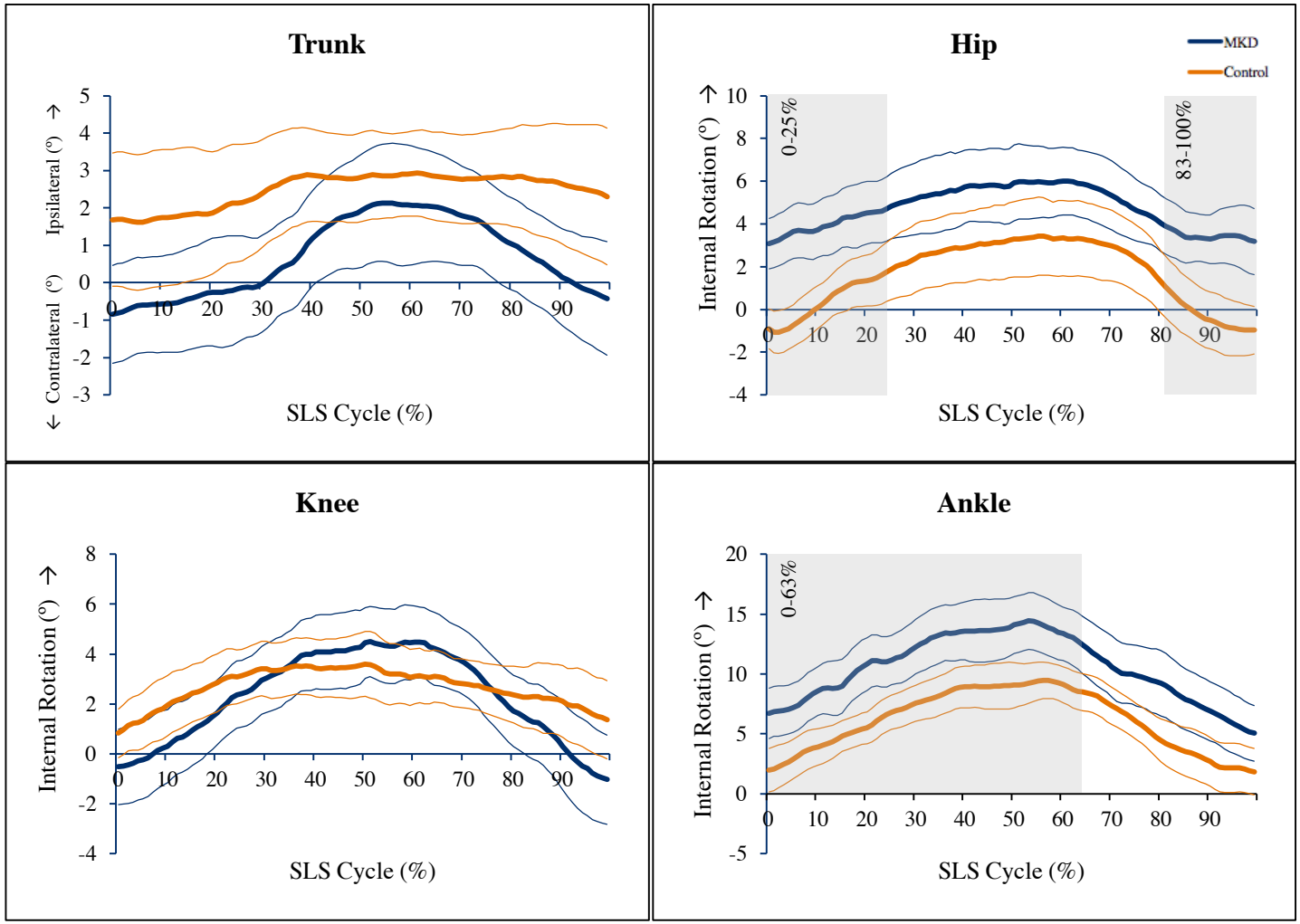


Figure 2-5a. Time Series Curve Analysis for Normalized Surface Electromyography (sEMG) Amplitudes During the SLS

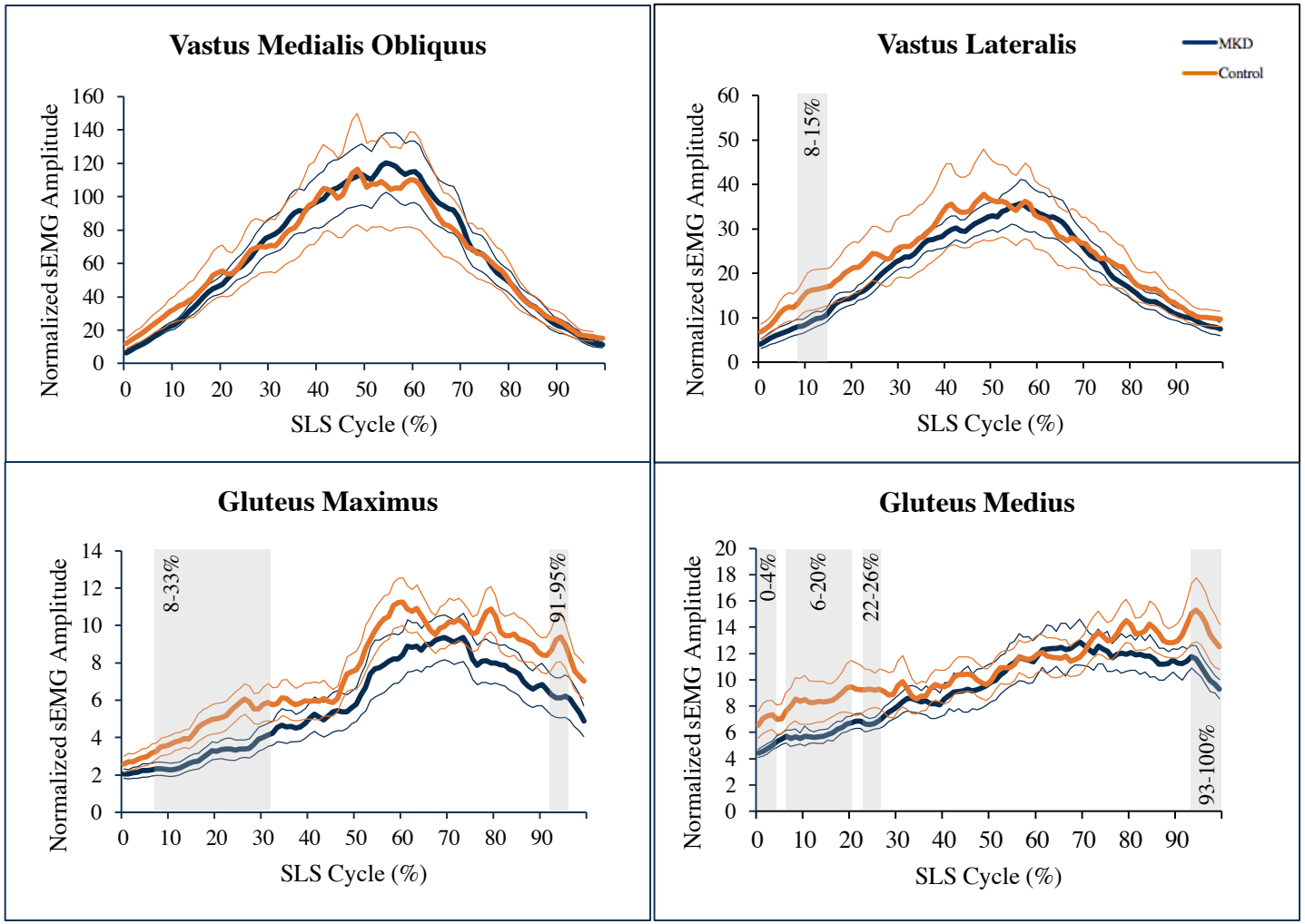


Figure 2-5b. Time Series Curve Analysis for Normalized Surface Electromyography (sEMG) Amplitudes During the SLS

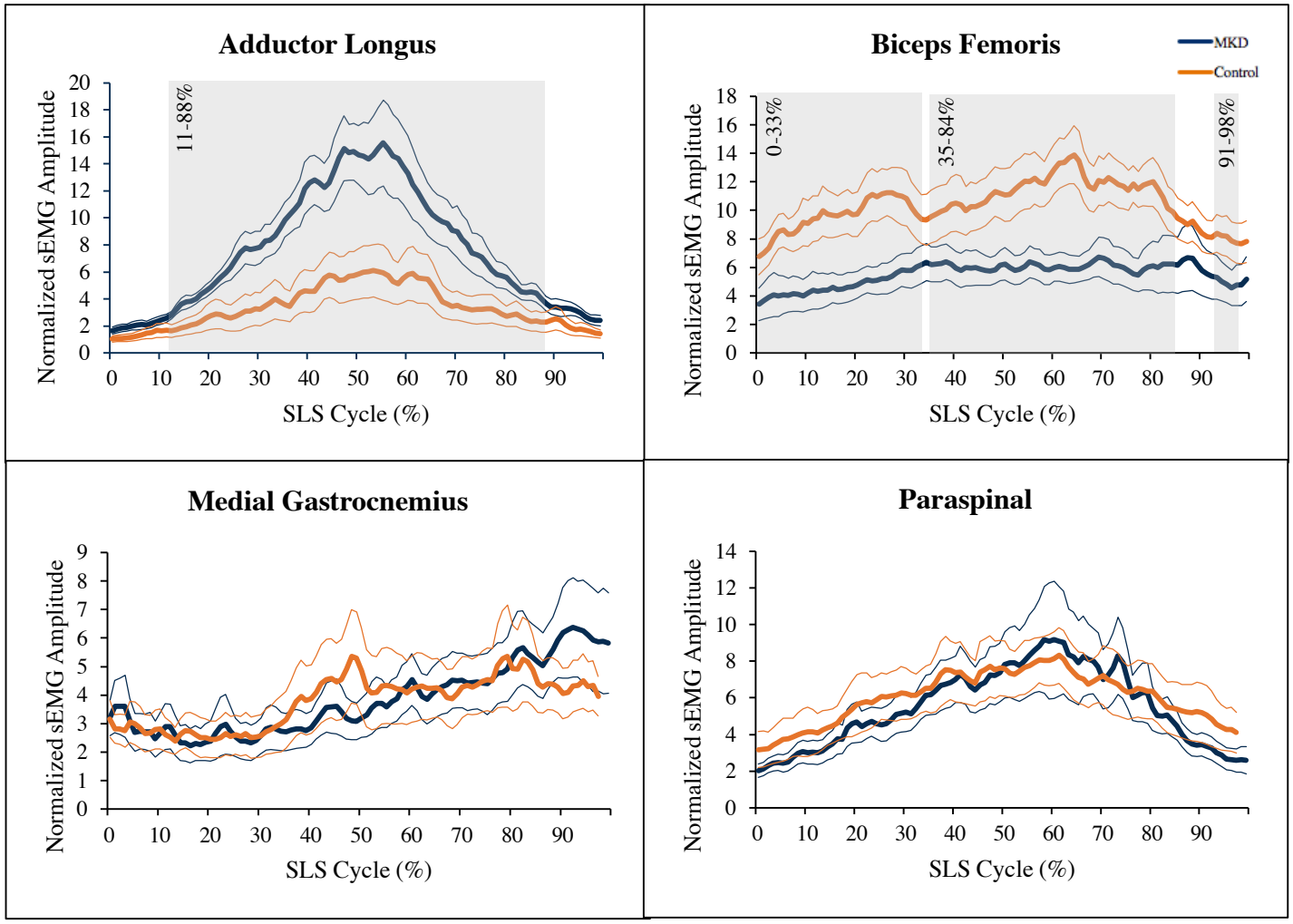


Figure 2-6. Mean Muscular Co-Activation Ratio Between Adductor Longus and Gluteus Medius During the SLS

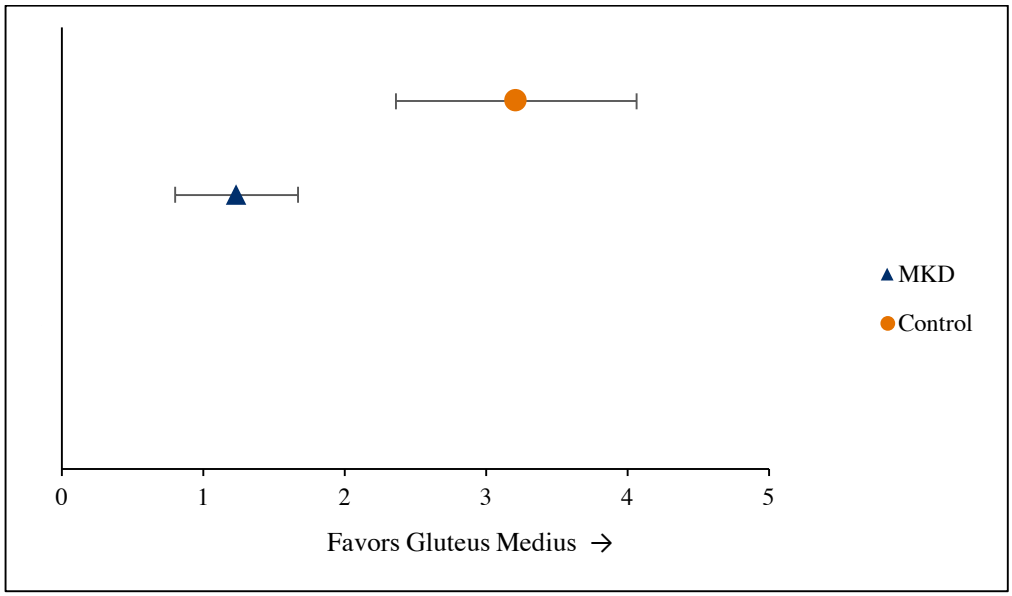
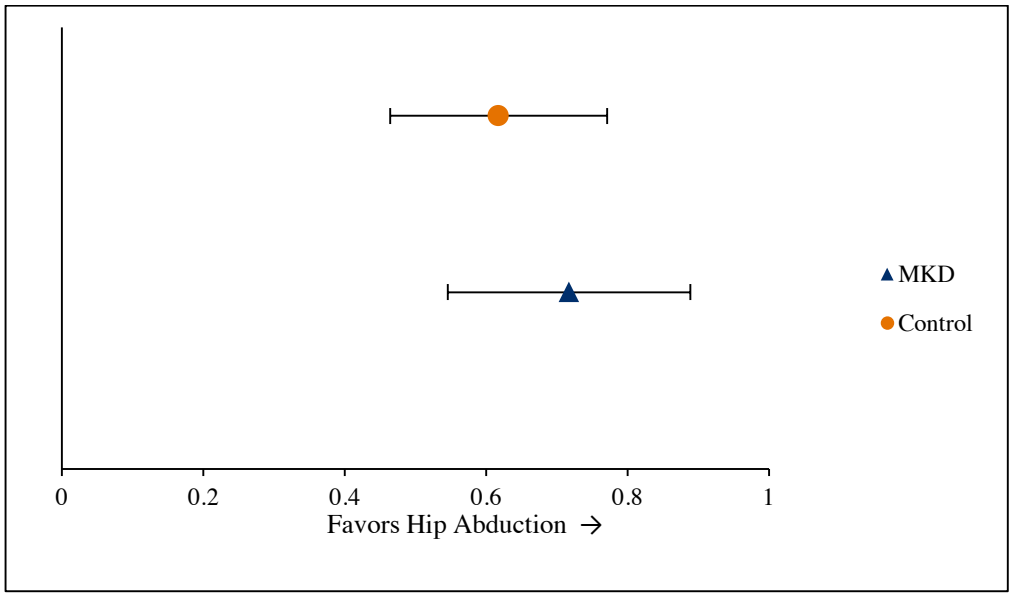


Figure 2-7. Mean Isometric Strength Ratio Between Hip Abduction and Hip Adduction



SECTION II: MANUSCRIPT III

THE EFFECT OF VISUAL BIOFEEDBACK ON LANDING KINEMATICS IN INDIVIDUALS WITH MEDIAL KNEE DISPLACEMENT

ABSTRACT

Background: Intervention studies that have successfully reduced knee injury risk have included feedback in some form. There is limited research on the integration of feedback into single leg tasks, and the utilization of "skill transfer" - ability to train one task and test another. The purpose of this study was to determine if the addition of real-time visual biofeedback to traditional lower extremity exercises improves single leg landing mechanics in females with MKD.

Methods: Twenty-four recreationally active females with MKD volunteered to participate in this study. Participants completed 3 trials of the single leg drop vertical jump (SL-DVJ) on the leg of interest, while triplanar kinematics at the trunk, hip, knee and ankle were collected via 3-dimensional motion capture. Individuals were randomized to the feedback or control group, and subsequently completed lower extremity exercises with or without visual feedback on knee valgus motion, respectively. Following the exercises, participants completed 3 additional trials of the SL-DVJ, identical to their baseline testing.

Results: After the intervention, the feedback group exhibited 13.03º more knee flexion compared to the control group during the flight phase. The feedback group also demonstrated 6.16º less knee valgus for the 200ms following initial contact, and a decrease in peak valgus excursion of 3.02° compared to their baseline values (p=.008), with a large meaningful effect.

Conclusions: Real-time visual feedback can immediately improve faulty lower extremity kinematics related to knee injury risk. Individuals with MKD were able to make

adjustments after only one training session, that reduced their knee valgus motion during a SL-DVJ task.

Word Count: 255

Key Words: Biofeedback, Corrective Exercise, Dynamic Knee Valgus

INTRODUCTION

Aberrant neuromuscular control has been identified as a contributor to lower extremity risk. In particular, altered peak lower extremity kinematic variables captured during functional tasks have been commonly identified in those who go on to suffer noncontact knee injuries.[1-4] Increased frontal plane knee motion during functional tasks, otherwise known as "dynamic knee valgus" (DKV), has been established as a predictor for non-contact ACL (NC-ACL) injury[2,5,6] and patellofemoral pain (PFP).[4,7,8]

Females suffer up to six times more NC-ACL injuries[9] and are twice as likely to develop PFP[10] than males. Additionally, females have demonstrated greater maximum knee valgus angle and total knee valgus motion during dynamic activities, which is consistent with the DKV movement pattern. Hewett et al. has theorized that landing with the knee in a valgus position decreases joint stability, making the knee more susceptible to injury.[11] Ford et al. has suggested that this biomechanical alteration is one of the reasons why females suffer more NC-ACL injuries compared to males.[1]

Injury prevention programs have been developed and implemented with the goal of correcting these faulty lower extremity biomechanics, particularly in female athletes. Their success in decreasing injury risk[12-14] can be attributed to an emphasis placed on correct landing techniques[11,15] and increasing lower extremity strength[13,16] & proprioception.[2,5] Identifying individuals that display medial knee displacement (MKD) on visual screenings[17-19] may provide insight into who may be at a heightened risk and would benefit the most from intervention. Additionally, the inclusion of multiple neuromuscular training components[13,20] (i.e. plyometrics, strength training, balance and core stability training, and feedback) may optimize the effectiveness of these programs. A

meta-analysis on neuromuscular prevention programs concluded that those including feedback and analysis of technique during functional tasks decreased ACL injury risk, whereas those that did not include feedback found no risk reduction.[21]

Cognitive function has been cited as an integral component to the transfer of learned movement from a controlled to a more dynamic environment.[22] The utilization of feedback in training or rehabilitation sessions promotes problem solving and intrinsic learning, and is an effective method to enhance the learning of new movement patterns.[16,23,24] Visual feedback has been implemented in either real-time (RTF) or post-response to target neuromuscular alterations. RTF provides individuals the opportunity to observe their movements and to make immediate biomechanical alterations, which may be an improvement on traditional post-response methods, where feedback is provided after the task is completed. Positive alterations to lower extremity kinematics have been demonstrated when RTF is implemented during both tuck jump[25,26] and jump-landing tasks,[27-30] however clinicians frequently prescribe corrective exercises that are slow, low intensity, and repetitive. There is little to support the use of visual feedback to alter the mechanics of tasks in which the participants are not trained.[31] Additionally, much of the evidence using RTF to improve mechanics associated with knee injury risk has evaluated outcomes using bilateral tasks,[25,31,32] although numerous athletic movements occur on single leg (i.e. landing, cutting). Furthermore, researchers have evaluated this intervention in healthy participants,[24,26,30,31] but have yet to establish its use in a population demonstrating kinematic risk factors.

The purpose of this study was to determine if the addition of visual biofeedback to traditional lower extremity exercises improves single leg landing mechanics in females with MKD.

METHODS

Study Design:

A randomized controlled laboratory study was conducted to evaluate the influence of a single session of exercise with visual biofeedback on lower extremity kinematics in individuals with clinically observed MKD. The independent variables included group (feedback, control) and time (pre-intervention, post-intervention); and the dependent variables were 3-dimensional lower extremity kinematics throughout 100% of the single leg drop vertical jump (SL-DVJ) task.

Participants:

Twenty-four recreationally active (self-reported, 30 minutes/day for at least 3 days/week) females between the ages of 15 and 40 years, with the presence of visually observed MKD,[33] were recruited from the local university community setting. The SLS test was utilized to determine if the MKD movement pattern was present. Participants stood on one limb with their opposite knee flexed to approximately 90° and hands folded across their chest. They were instructed to squat down as low as comfortably possible for two seconds and to return to the starting position for two seconds. A metronome was utilized to ensure consistency in the duration of the task, and a 30-second rest period was provided between each trial. Both limbs were screened with the SLS test for MKD. Participants were considered to have MKD if the midpoint of the patella crossed medial

to the 1st ray in at least 3 of 5 SLS trials. If a participant presented with MKD on both sides, the limb of interest was randomly selected.

Exclusion criteria consisted of any known neurological condition resulting in a decrease in balance and/or proprioception, infection near the trunk or lower limbs, or known pregnancy. For the purposes of this study, we did not exclude history of lower extremity injury, as long as the participant was able to complete the tasks during the testing session. There were no differences in participant demographics between groups (Table 3-1). This study was approved by the University of Virginia's Institutional Review Board (IRB-HSR #18570), and all participants provided written, informed consent prior to enrollment.

Instruments:

Three-dimensional joint kinematics of the trunk, hip, knee, ankle were measured with a 12-camera motion analysis system (Vicon Motion Systems, Oxford, UK), and Motion Monitor software (v. 9, Innovative Sports Training, Inc., Chicago, IL, USA) at a sampling rate of 250 Hz. Thirty-two retroreflective markers (14mm) were configured in eight clusters of four, and secured on semi-rigid thermoplastic plates. Clusters were affixed bilaterally over the dorsum of the foot, the lateral shank, the lateral thigh, the sacrum, and the thoracic spine with elastic tape. Height and mass were collected, and joint centers were digitized utilizing the stylus. A non-conductive force plate (Bertec Corporation, Columbus, Ohio, USA) with a sampling rate of 1000 Hz was used to determine initial contact during the SL-DVJ.

Visual feedback was provided for the feedback group through a Microsoft Kinect™ camera system. All data were collected at 30Hz and processed real-time

utilizing VirtualCoach software (Kinetech Labs, Inc., Charlottesville, VA, USA), a custom Visual Studio (Community 2015, Microsoft Corp., Redmond, WA, USA) program, to provide feedback on the knee valgus angle during the exercise trials. The Microsoft Kinect sensor was positioned 140cm from the center of the testing area, at a height of 70cm, facing anterior to the participant. If it was noted during a trial that the participant exited the Kinect's field of view, the researcher adjusted the sensor as necessary, and discounted the previous repetition.

Procedures:

Individuals who met the inclusion & exclusion criteria were enrolled into the study. Procedures are outlined in a CONSORT flow chart in Figure 3-3. After enrollment, participants were set-up for motion analysis, and a 5-second bipedal quiet standing trial was recorded for kinematic normalization. Individuals then performed the SL-DVJ task[18] with the leg of interest from a 10-cm box, positioned at the leading edge of the forceplate. They were instructed to drop forward toward the force plate and to transition to a maximal vertical jump upon ground contact. A target was provided directly above the force plate to minimize forward or lateral trajectory.[34] Participants were allotted as many practice trials as necessary to ensure proper form, and a total of 3 SL-DVJ trials were collected and utilized for analysis.

Participants in both groups (control, feedback) completed 4 exercise tasks immediately following baseline testing of the SL-DVJ (Figure 3-2). Exercises included the double leg squat, single leg squat, single leg step down, and lateral step down, and were selected due to their utilization in the clinical setting, and their slow, low intensity and repetitive nature. Ten repetitions of each exercise were completed, and the single

limb exercises were conducted on the limb of interest only. Participants in the feedback group viewed a real-time digital model of their body segments during the exercise tasks. The skeletal model generated by the Microsoft Kinect™ changed color as a result of the knee valgus angle[2] in the limb of interest (≥8º = red, 5-7.9º = yellow, <5º = green) and was projected onto a monitor for visualization (Figure 3-3). Participants in the feedback group were instructed to control their medial knee motion to perform the exercises in the "green" category. Participants in the control group did not receive any feedback during the exercises

All participants completed post-exercise assessment immediately following the intervention. Identical testing procedures were conducted for kinematics during the SL-DVJ baseline assessment.

Data Processing:

Kinematic analyses were performed beginning 100ms prior to initial contact, through 200ms after initial contact. Initial contact was defined as the time at which the vertical ground reaction force exceeded 20N. The 300ms time epochs were reduced to 100 frames, so that each frame represented 1% of the task, and the mean of the three trials was used for analysis. Data were filtered with a 4th order low-pass Butterworth filter at a cutoff frequency of 14.5 Hz, and normalized to kinematics at quiet standing. Joint rotations for the trunk, hip, knee, and ankle were calculated using the Euler rotation method (Y, X', Z'').

Statistical Analysis:

Continuous Analysis

Time series curve analyses were constructed for normalized lower extremity kinematics across 100% of the SL-DVJ. Group means and associated 90% confidence intervals were plotted for the entire task. Areas where the confidence intervals did not overlap between the two groups (feedback and control) for at least three consecutive percentage points were considered statistically significant.

Discrete Analysis

Three-dimensional kinematic peaks were extracted and compared to kinematics at quiet standing to calculate total kinematic excursions during the 300ms time epoch. A 2x2 mixed model ANOVA was conducted. The between factor was group (control and feedback) and the within factor with repeated measures was time (pre/post intervention). The level of significance was set *a priori* at $p < 0.05$ for all analyses, and we chose not to control for multiple comparisons, as recommended by Hopkins et al.[35] Cohen's d effect sizes and associated 95% confidence intervals were also calculated to estimate the magnitude of difference between the two groups. Effect sizes were interpreted as ≥ 0.80 large, $0.50 - 0.79$ moderate, $0.20 - 0.49$ small, and < 0.20 trivial.[36] All data were analyzed with SPSS statistical software (v. 24.0, SPSS, Inc., Chicago, IL, USA).

RESULTS

Continuous Analysis:

A significant difference between the control and feedback groups existed at baseline, where the feedback group was 3.83º more everted the first 17% immediately following initial contact. No other significant differences were observed between groups prior to the intervention (Figures 3-4 to 3-6). After the intervention, the feedback group exhibited a 13.03º increase in knee flexion during the first 100ms prior to initial contact

(0-31% of the task), and a 6.16º decrease in knee valgus for the 200ms following initial contact (34-100%). No other significant differences were observed between groups after the intervention (Figures 3-7 to 3.9).

Discrete Analysis:

A time main effect was observed for hip adduction (p=0.030), where both the feedback group (pre: 9.34º ± 4.17, post: 10.30º ± 1.89; effect size: 0.30 (-0.51 to 1.10)) and control group (pre: 9.90º ± 3.78, post: 11.90º ± 5.21; effect size: 0.44 (-0.37 to 1.25) increased peak adduction excursion after the intervention. No group main effects were observed for peak kinematic excursions. Significant group by time interactions existed in hip flexion, trunk ipsilateral rotation, and knee valgus. The feedback group decreased hip flexion (pre: 34.74º ± 15.16, post: 30.10º ± 12.14; effect size: -0.33 (-1.14 to 0.47)), while the control group increased hip flexion (pre: 33.92º ± 11.14, post: 38.15º ± 12.21; effect size: 0.36 (-0.44 to 1.17). Similarly, the feedback group decreased trunk ipsilateral rotation (pre: 6.15º ± 1.73, post: 5.38º ± 1.65; effect size: -0.19 (-0.99 to 0.61), while the control group increased ipsilateral rotation (pre: 4.98º ± 2.75, post: 7.12º ± 4.09); effect size: -0.20 (-1.43 to 0.24). Finally, the feedback group decreased knee valgus (pre: 7.95º ± 3.80, post: 4.93º ± 1.64; effect size: -1.03 (-1.88 to -0.18), while the control group increased knee valgus (pre: 6.98º ± 2.99, post: 8.04º ± 3.85; effect size: -0.31 (-0.50 to 1.11). The only observed meaningful change was the decrease in knee valgus in the feedback group, as there was a large effect with a confidence interval that did not cross zero (Tables 3-2 & 3-3).

DISCUSSION

The purpose of this study was to determine if traditional lower extremity exercises augmented with visual feedback on knee valgus angle improved landing kinematics during the SL-DVJ. We found an improvement in knee frontal and sagittal plane kinematics in those individuals who received visual feedback.

After the intervention, the feedback group performed the SL-DVJ with an average decrease of 6.16º knee valgus during the last 200ms of the task (post initial contact), then the control group (Figure 3-8). Additionally, the feedback group exhibited less peak knee valgus excursion after the intervention, with a large meaningful effect (Table 3-2). These findings are similar to other studies that have used RTF to correct lower extremity kinematics. Nyman et al.[28] observed a significant improvement in knee separation distance, a surrogate for knee valgus angle, during landing in young female gymnasts. These athletes were trained with feedback on their knee position during the DVJ, and also tested during the same task. While Ericksen et al.[24] did not see lasting changes during a 4-week feedback program focused on the DVJ task, the researchers did not screen for faulty kinematic movement prior to intervening. As a result, potential differences may have been masked by those participants who did not have a faulty movement pattern at baseline.

In addition to kinematic feedback, RTF based on joint kinetics has also been utilized, however the results have been inconsistent.[31,32] Beaulieu et al. did not see any changes in landing mechanics after 2 sessions of RTF on knee abduction moment during the DVJ. In a pilot study, Ford et al. compared kinematic and kinetic focused RTF provided during double leg squats, and found that the kinetic feedback was successful in improving both knee abduction moment and maximum knee valgus angle during the DVJ

task. This was the first study that found improvements utilizing the concept of "skill transfer", where the participants trained different tasks in which they were tested. However, the researchers had a small sample size (n=4), and only evaluated peak biomechanical variables versus assessing throughout the entire task. The results of the present study were similar, albeit with a different form of RTF.

The feedback group exhibited significantly more knee flexion prior to initial contact than the control group after the intervention. When participants were both tested and trained with dynamic and plyometric tasks, researchers observed similar findings after initial contact.[28] As we did not observe sagittal plane differences between groups after initial contact, this finding could be attributed to preparation for the landing, and may correspond with the decrease in knee valgus exhibited by this group. The individuals who received the feedback may be adjusting the strategy utilized to place themselves in a better position for the landing. Chappell et al.[37] observed that females tend to exhibit less knee and hip flexion in the flight phase before landing as compared to males, and hypothesized that this finding could relate to a difference in ACL loading during landing. Our sagittal plane findings at the knee prior to initial contact could potentially decrease these forces at the knee upon landing.

The feedback technique utilized in this study did not require the use of a motion capture laboratory. The Microsoft Kinect™ is a cost-effective piece of technology, which has been shown to have excellent measurement properties when compared to the gold standard 3D motion capture.[38,39] The effectiveness of this method shows great potential for implementation in a variety of clinical or sport-specific environments. Furthermore, the eventual transition to an intervention resembling "game-based therapy" may improve

participant engagement and compliance, and serve to target multiple kinematic risk factors in a longer intervention program. RTF using gaming systems has already shown to be an effective tool in balance training,[40,41] and through this study we have demonstrated its utility during lower extremity exercises traditionally utilized in a rehabilitation or for corrective exercise.

This study was not without limitations. While this is the first study to evaluate the concept of skill transfer in combination with visual feedback aimed at improving lower extremity kinematics in individuals with MKD, only the immediate effects of the intervention were analyzed. It is unknown how long these alterations are retained for, and how many sessions are needed to make permanent changes to dynamic movement strategies. Future studies should evaluate long-term acquisition and retention of movement pattern alterations, and seek to incorporate this intervention into neuromuscular training and injury prevention programs.

CONCLUSIONS

The results of this study indicate that RTF can exhibit immediate improvements in aberrant kinematics. Individuals with visually observed MKD were able to make adjustments after only one training session, that reduced their knee valgus motion during a single leg landing task.

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Table 3-1. Feedback and Control Group Participant Demographics

	Feedback (n=12)	Control (n=12)	p-value
Age (yrs)	19.75 (0.87)	19.75 (0.97)	0.860
Height (cm)	165.32 (8.69)	166.98 (6.89)	0.183
Mass (kg)	62.41 (8.91)	59.98 (6.24)	0.474

yrs = years, cm = centimeters, kg = kilogram

Table 3-2. Pre-Post Intervention SL-DVJ Hip and Trunk Peak Kinematic Excursions and Cohen's d Effect Sizes with 95% Confidence Intervals

	Feedback Group			**Control Group**			**Time Main Effect** p-value	**Group Main Effect** p-value	**Group x Time Interaction** p-value
	Pre Mean (SD)	Post Mean (SD)	ES (LL, UL)	Pre Mean (SD)	Post Mean (SD)	ES (LL, UL)			
Hip Flexion (º)	34.74 (15.16)	30.10 (12.41)	-0.33 (-1.14,0.47)	33.92 (11.14)	38.15 (12.21)	0.36 (-0.44,1.17)	0.853	0.487	0.001*
Hip Adduction (º)	9.34 (4.17)	10.30 (1.89)	0.30 (-0.51,1.10)	9.90 (3.78)	11.90 (5.21)	0.44 (-0.37,1.25)	0.030*	0.474	0.420
Hip IR (º)	12.40 (4.70)	10.58 (4.52)	-0.22 (-1.02,0.58)	11.61 (4.26)	11.93 (5.81)	0.06 (-0.74,0.86)	0.394	0.878	0.229
Trunk Flexion (º)	7.56 (4.42)	8.54 (3.71)	0.14 (-0.66,0.95)	7.98 (2.99)	8.03 (2.63)	0.02 (-0.78,0.82)	0.367	0.973	0.422
Trunk Ipsilat. Flexion (º)	3.86 (2.20)	4.51 (2.45)	0.18 (-0.62,0.99)	4.94 (3.85)	4.14 (1.82)	-0.27 (-1.07,0.54)	0.887	0.712	0.203
Trunk Ipsilat. Rotation (º)	6.15 (1.73)	5.38 (1.65)	-0.19 (-0.99,0.61)	4.98 (2.75)	7.12 (4.09)	-0.20 (1.43,0.42)	0.114	0.785	0.002*

* = Significant difference between control and MKD groups at $p < 0.05$

A positive effect size indicates an increase in kinematic excursion after intervention

SD=Standard Deviation, UL=Upper Limit, LL=Lower Limit, IR=Internal Rotation, Ipsilat = Ipsilateral

Table 3-3. Pre-Post Intervention SL-DVJ Ankle and Knee Peak Kinematic Excursions and Cohen's d Effect Sizes with 95% Confidence Intervals

	Feedback Group			**Control Group**			**Time Main Effect** p-value	**Group Main Effect** p-value	**Group x Time Interaction** p-value
	Pre Mean (SD)	Post Mean (SD)	ES (LL, UL)	Pre Mean (SD)	Post Mean (SD)	ES (LL, UL)			
Ankle Dorsiflexion (º)	46.80 (6.60)	45.94 (13.07)	-0.08 (-0.88,0.72)	49.45 (5.47)	49.78 (10.16)	0.04 (-0.76,0.84)	0.922	0.245	0.825
Ankle Eversion (º)	9.08 (2.30)	10.85 (2.09)	0.81 (-0.03,1.64)	10.18 (4.83)	11.28 (5.42)	0.21 (-0.59,1.02)	0.242	0.490	0.781
Ankle IR (º)	15.32 (7.59)	17.73 (6.21)	0.34 (-0.46,1.15)	15.69 (6.36)	17.37 (8.03)	0.23 (-0.57,1.03)	0.038*	0.998	0.698
Knee Flexion (º)	43.26 (9.81)	42.89 (7.54)	-0.04 (-0.84,0.76)	47.32 (10.28)	52.45 (7.08)	0.58 (-0.24,1.40)	0.103	0.051	0.062
Knee Valgus (º)	7.95 (3.80)	4.93 (1.64)	-1.03 (-1.88,-0.18)	6.98 (2.99)	8.04 (3.85)	0.31 (-0.50,1.11)	0.176	0.342	0.008*
Knee IR (º)	8.09 (3.23)	6.99 (3.65)	-0.32 (-1.12,0.49)	7.72 (2.41)	8.45 (2.81)	0.28 (-0.53,1.08)	0.833	0.516	0.326

* = Significant difference between control and MKD groups at $p < 0.05$
A positive effect size indicates an increase in kinematic excursion after intervention
SD=Standard Deviation, UL=Upper Limit, LL=Lower Limit, IR=Internal Rotation

Figure 3-1. CONSORT Flowchart

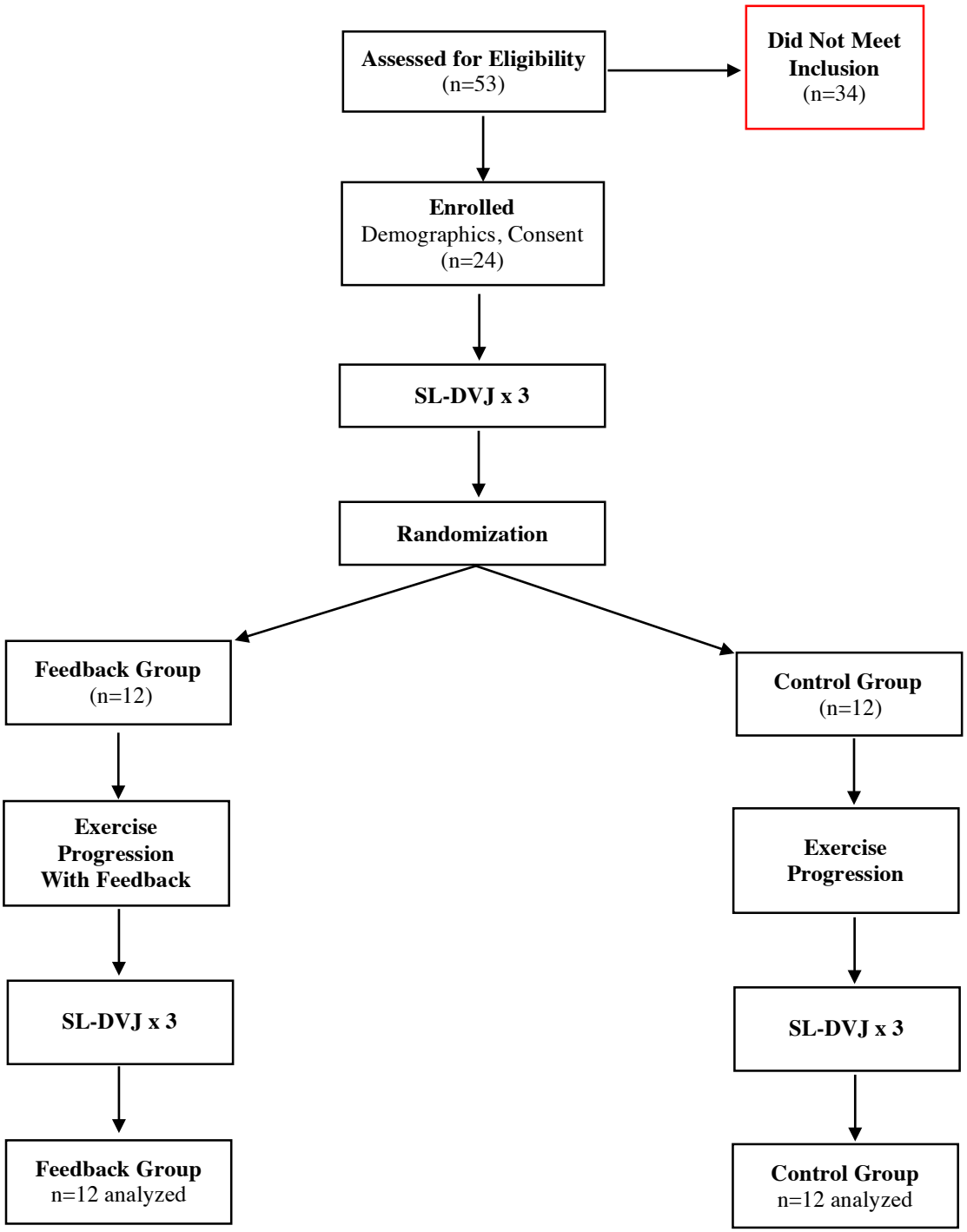


Figure 3-2. Exercise Progression

Figure 3-3. Kinect Visual Feedback

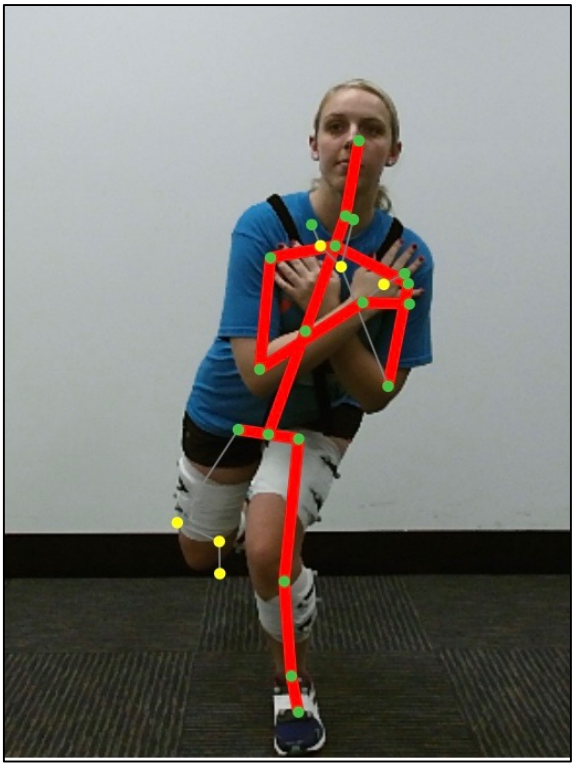


Figure 3-4. Time Series Curve Analysis for Sagittal Plane Kinematics During the SL-DVJ at Baseline

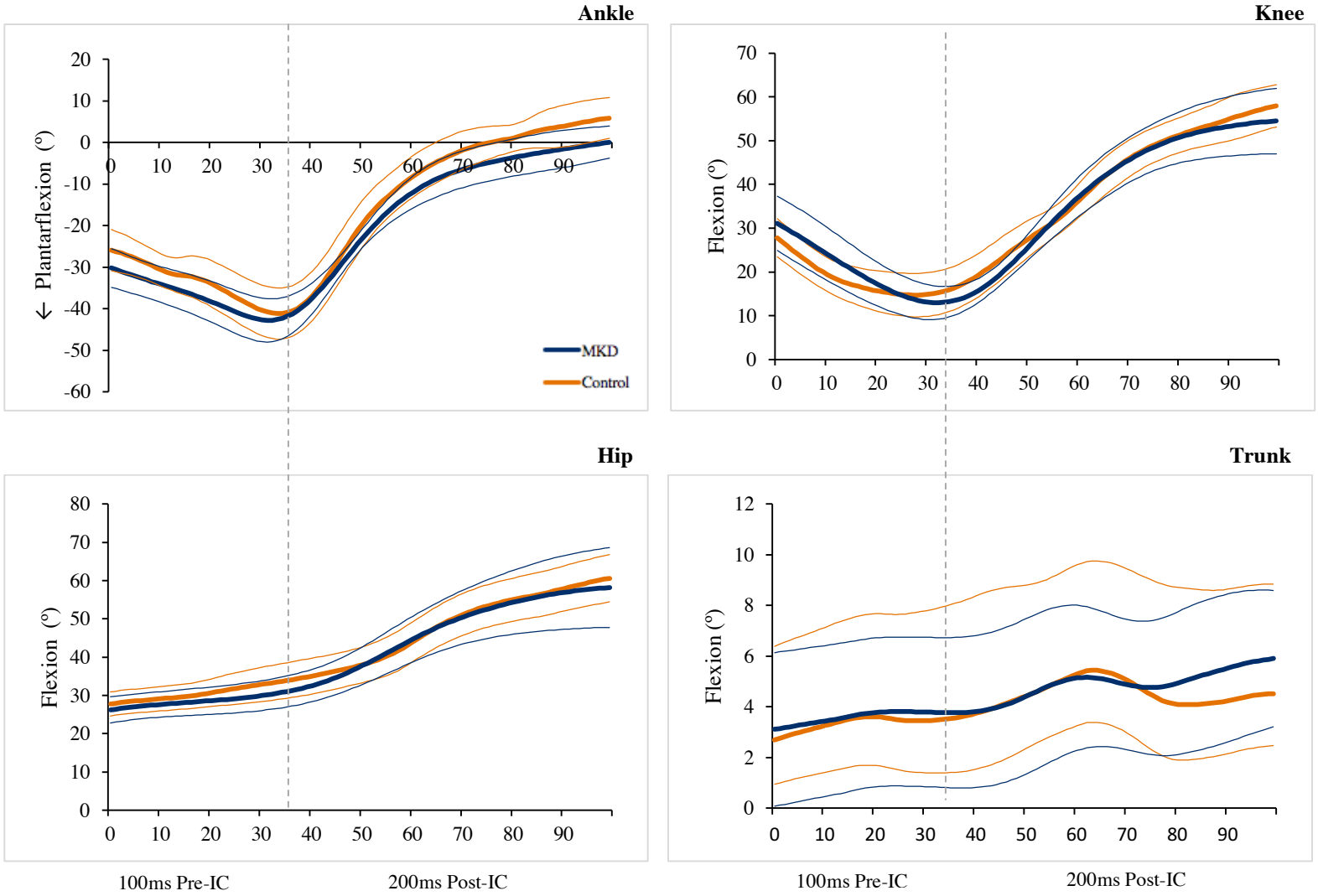


Figure 3-5. Time Series Curve Analysis for Frontal Plane Kinematics During the SL-DVJ at Baseline

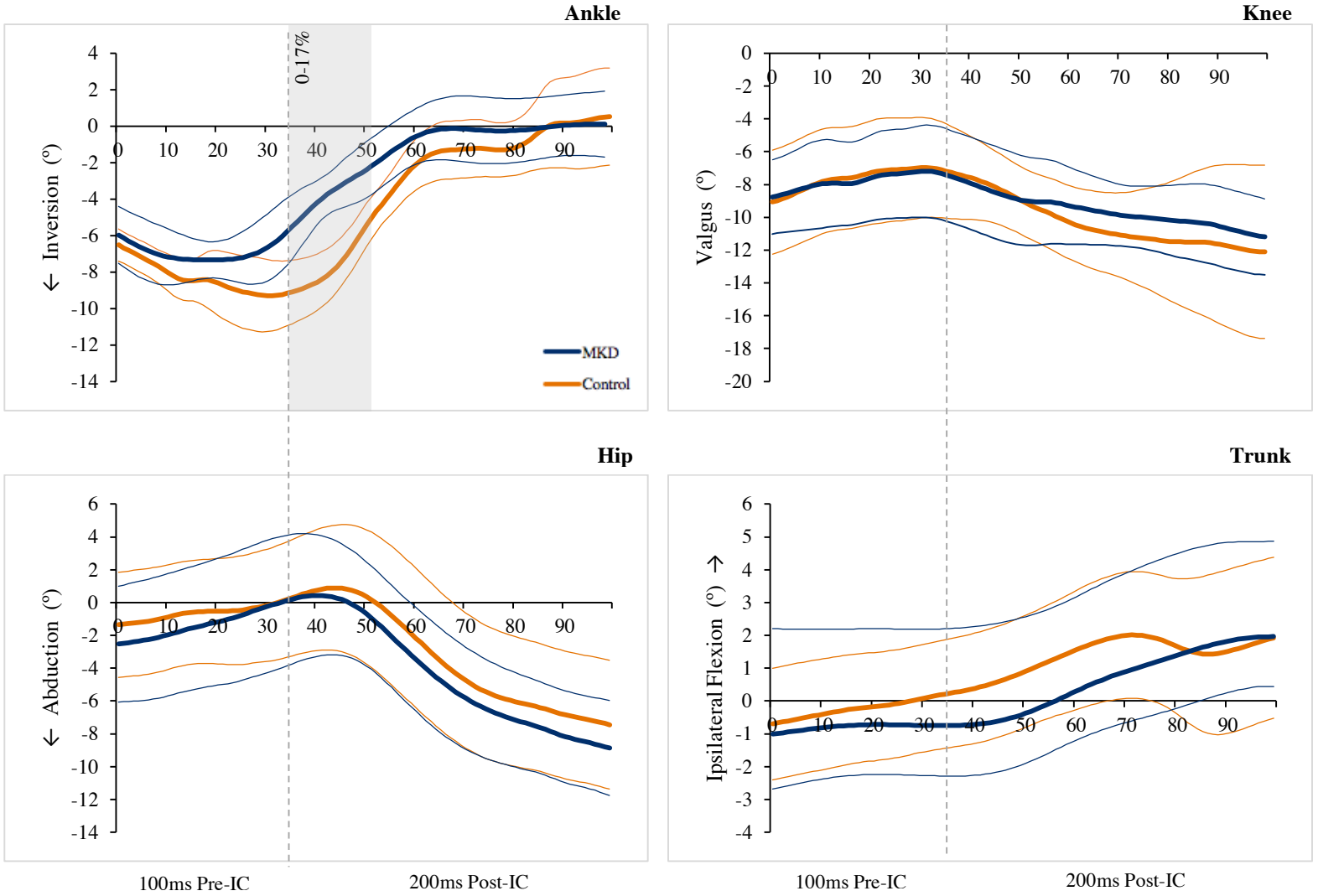


Figure 3-6 Time Series Curve Analysis for Transverse Plane Kinematics During the SL-DVJ at Baseline

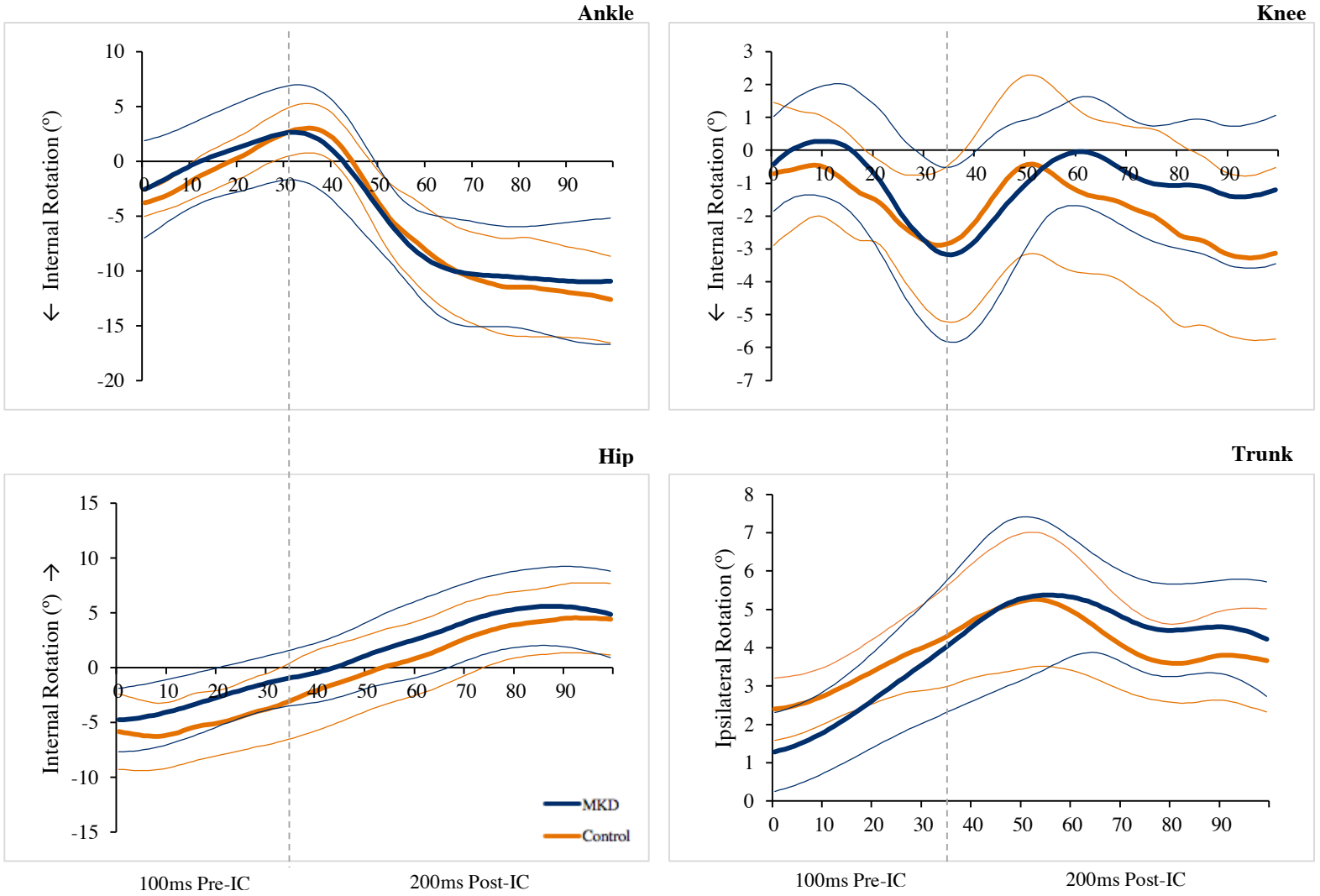


Figure 3-7. Time Series Curve Analysis for Sagittal Plane Kinematics During the SL-DVJ After Intervention

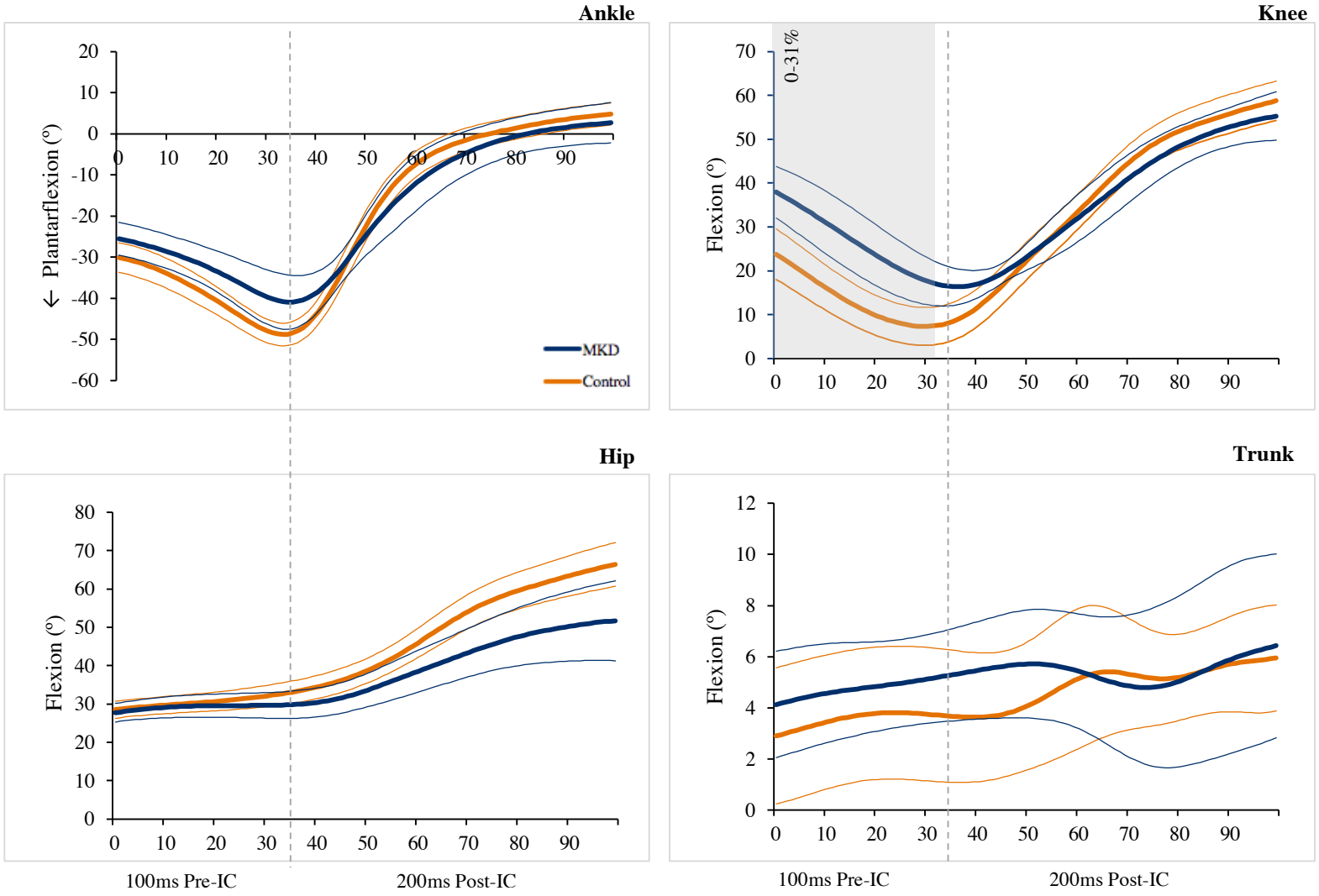


Figure 3-8. Time Series Curve Analysis for Frontal Plane Kinematics During the SL-DVJ After Intervention

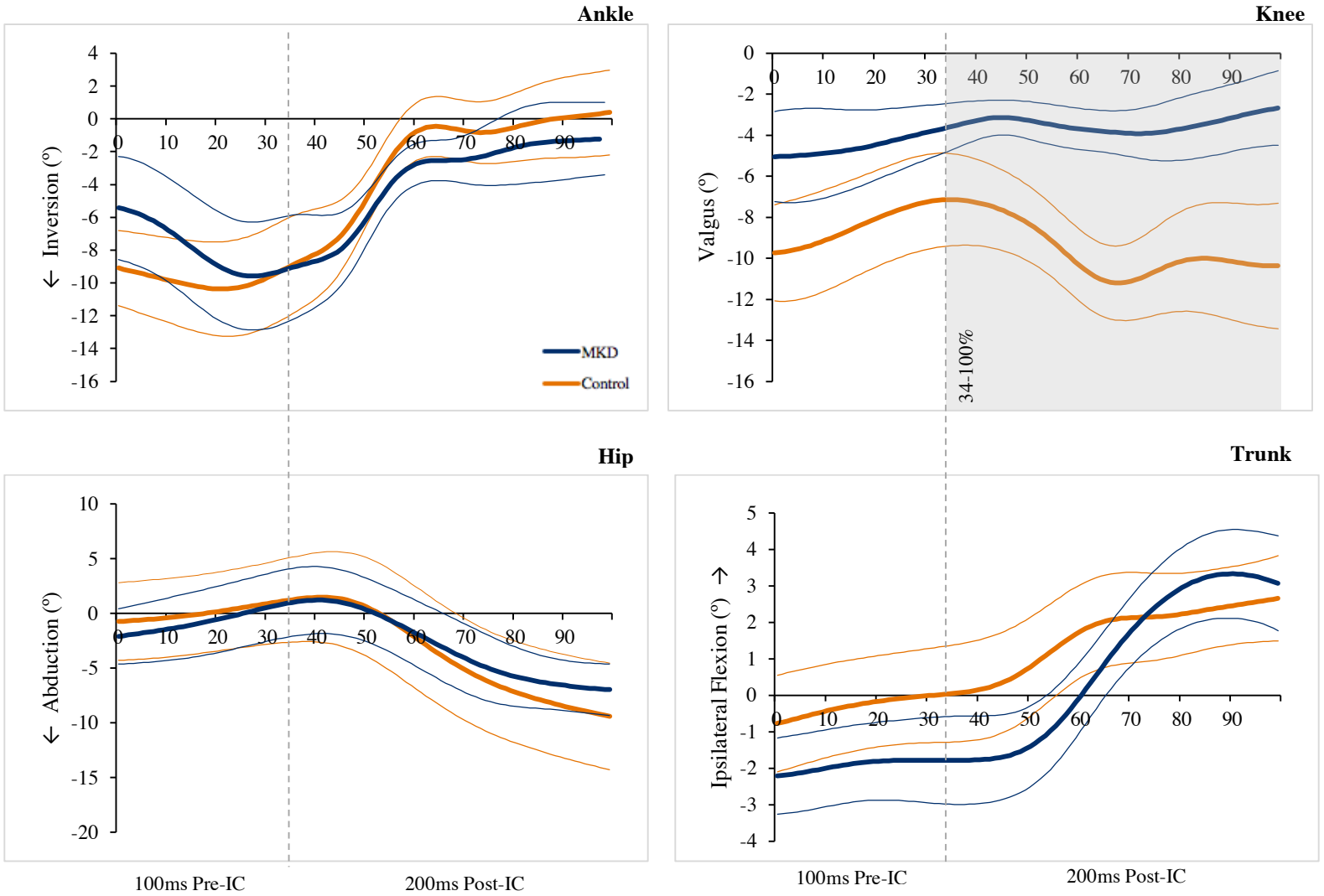
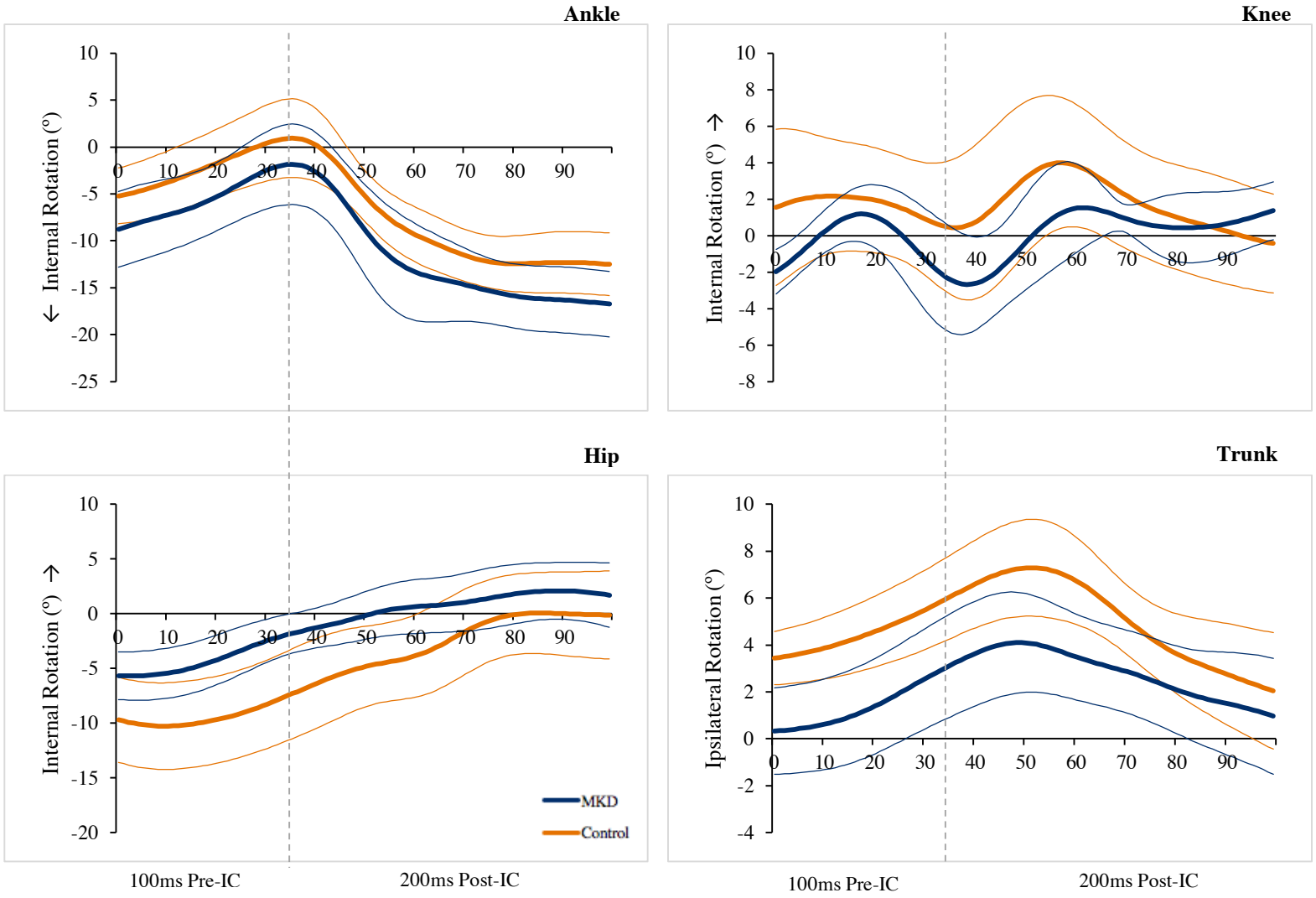


Figure 3-9. Time Series Curve Analysis for Transverse Plane Kinematics During the SL-DVJ After Intervention



APPENDIX A
The Problem

Problem Statement

The knee is the second most common lower extremity injury,[1] and the most common resulting in ten or more days of time loss.[2] Consequently, both acute and chronic injuries to this joint have been shown to have a significant impact on performance.[3-5] Deficits have been identified in both healthy individuals, and those who return after ACL reconstruction,[6] thus increasing risk for both primary and secondary injury.[6,7]

Field-based movement screenings are frequently utilized to identify "high risk" individuals.[8,9] In particular, screenings that identify strategies resulting in high knee loads across multiple planes are the most effective in classifying knee injury risk.[10,11] While functional screenings, such as the Landing Error Scoring System[12], Functional Movement Screening,[13] and overhead squat[14] have been validated in community settings, athletes often engage in unilateral tasks when competing. Similarly, clinicians frequently utilize the single leg squat as a screening for dysfunctional movement, through the observation of medial knee displacement. However, this test has not been validated against a 3-dimensional motion analysis system, and individuals with and without medial knee displacement based on this screening have not been evaluated to determine if specific movement strategies exist within each group.

Injury prevention programs are often implemented in athletic populations with the goal of reducing noncontact knee injury risk. The programs that have shown the greatest success have all incorporated some form of feedback into their design.[7] Through improved retention and the transfer of safe motor skills, these programs have increased their effectiveness and efficiency.[15,16]While positive changes have been observed when real-time visual feedback is implemented during dynamic tasks, such as the jump-

landing,[17,18] or tuck jump,[19,20]similar results have not been observed during traditional lower extremity exercises that are slow and repetitive.

Therefore, the specific aims for this study are:

- To compare the single leg squat visual observation test with the gold standard 3-dimensional motion analysis based on the ability to determine excessive frontal plane knee motion.
- To compare lower extremity single leg squat mechanics between individuals with and without excessive frontal plane knee motion, determined by the visual observation test.
- To determine if visual biofeedback can alter lower extremity mechanics in individuals with excessive frontal plane knee motion.

Research Questions:

1. Is the single leg squat visual screening a valid diagnostic test for knee injury risk as compared to 3-dimensional motion analysis?
   - *Hypothesis 1:* The single leg squat visual screening test will demonstrate high sensitivity (≥75%) for determining excessive medial knee displacement, as compared to 3-dimensional motion analysis.
   - *Hypothesis 2:* The single leg squat visual screening test will demonstrate high specificity (≥75%) for determining excessive medial knee displacement, as compared to 3-dimensional motion analysis.

2. Do kinematic, muscle activity, and hip strength contributions to the SLS movement strategy differ between individuals categorized with and without medial knee displacement on the visual single leg squat screening?
   - *Hypothesis 1:* Individuals with medial knee displacement will display greater hip adduction and hip internal rotation, knee valgus and knee internal rotation, than individuals without medial knee displacement, during the single leg squat than those without medial knee displacement.

- *Hypothesis 2:* Individuals with medial knee displacement will display greater hip adductor activity, and less gluteus medius activity during the single leg squat than those without medial knee displacement.
- *Hypothesis 3:* Individuals with medial knee displacement will display less gluteus medius isometric strength than those without medial knee displacement.

3. Does one session of visual biofeedback alter lower extremity kinematics during a single leg drop vertical jump in individuals with medial knee displacement compared to a control intervention?
    - *Hypothesis 1:* The visual biofeedback will decrease knee valgus joint angle during the single leg drop vertical jump
    - *Hypothesis 2:* The visual biofeedback will decrease hip adduction during the single leg drop vertical jump

Assumptions:

- Visual observation of medial knee displacement during a functional task is representative of excessive knee valgus.
- Retro-reflective markers affixed to the skin were indicative of motion of the underlying bony structures
- Kinematic motion during testing is similar to normal functional tasks
- Surface electromyography adequately represented the true activation of lower extremity musculature
- Quiet standing is a reliable and valid method of surface electromyography normalization
- Participants will provide maximal effort during testing sessions.
- Equipment will function properly and will be calibrated for each participant.
- Standardization of the rate of speed for the single leg squat will not influence the ability of participants to complete the task.
- History of injury would not affect the ability to complete the functional tasks.

Delimitations:

- Participants were recreationally active.[21]
- Participants were between 15 and 40 years old.
- Participants were able to complete functional tasks
- Maximal voluntary isometric contractions were utilized to establish electrode placement to minimize potential EMG cross talk for processing and data analysis
- A metronome was used during the single leg squat at a rate of 60 beats per minute.
- An average of 3 trials was utilized for the outcome measures.

Limitations:

- Participants in this study were young and physically active, which may limit the generalizability of these findings to the general population.
- Valgus threshold to determine level of risk on 3-dimensional motion analysis was based on a previously collected prospective study[22]

Operational Definitions:

- Area Under the Curve (AUC): The measure of predictive knee valgus utilized in receiver operating characteristic curve analysis. Greater AUC represents a stronger indicator of the positive outcome.
- Cutoff Point: The point on a receiver operating characteristic (ROC) curve at which the measure has the greatest diagnostic sensitivity and specificity (i.e. the most "northwest" point on the ROC curve graph).
- Dynamic Knee Valgus: Movement strategy during a functional task, involving frontal plane and transverse plane motion at the hip, knee, and ankle, and results in excessive knee valgus.
- Initial Contact: The first point during the single leg drop vertical jump (SL-DVJ) at which the vertical ground reaction force is greater than 20N.

- Medial Knee Displacement: Visual observation of the knee moving inward (towards the midline) during a functional task. When the center of the patella crosses medial to the first ray of the foot, an individual is considered to have medial knee displacement.[23,24]
- Peak Kinematic Excursion: The highest value recorded for joint angle during the task, normalized to the value at quiet standing.
- Normalized Muscle Activation: The muscle activation signal normalized to activation during quiet standing.
- Real-Time Feedback: Visual feedback provided at the same time that a functional task is completed, with the goal of immediate movement correction.
- Receiver Operating Characteristic (ROC) Curve: Graphical technique that compares the sensitivity and specificity of a diagnostic measure.
- Recreationally active: Participating in at least 30 minutes of moderate to vigorous physical activity 3-5 times per week.

Innovation:

Minimizing lower extremity injury risk is a priority for sports medicine professionals. This study aims to describe the lower extremity function of individuals with visually observed medial knee displacement. Clinically, the goal of identifying individuals displaying biomechanical characteristics consistent with increased risk for noncontact knee injury is two-fold. The primary goal is to identify a group to target with neuromuscular training or injury prevention programs. While previous research has focused on identifying noncontact knee injury risk factors utilizing 3-dimensional motion analysis (3DMA), the utility of a screening test with visual observation to identify the same risk has not yet been established. It is clear that 3DMA is a valid and reliable method of kinematic evaluation, however it is not a practical method for utilization in clinical environments. The secondary goal is to optimize intervention for individuals with medial knee displacement by integrating a visual feedback component to lower extremity exercise. When neuromuscular training programs are implemented, improvements in athletic performance, movement biomechanics, and reduced knee injury risk, however those considered “high risk” may need additional impairment-based components to

substantially reduce risk. Without further study on the visual observation of medial knee displacement, the utility of a screening to identify “high risk” individuals, and the potential interventions utilized for movement correction remains difficult for clinicians to have a clear understanding of noncontact injury risk reduction. A validated visual screening test will aid clinicians in better predicting which individuals to target with movement correction intervention, and how visual feedback may optimize lower extremity exercises.

APPENDIX B:
Literature Review

ETIOLOGY OF NONCONTACT KNEE INJURIES

Noncontact knee injuries commonly occur in physically active individuals. Amongst adolescent athletes, the knee is the most commonly injured joint with an estimated 2.5 million sports-related injuries occurring each year.[25] Consequently, these injuries result in a relatively high time-loss compared to other injuries.[1] In particular, active individuals are vulnerable to injury of the anterior cruciate ligament (ACL),[26,27] menisci, medial collateral ligament (MCL),[28-30] and to the development of overuse injuries such as patellofemoral pain (PFP).[31]

Non-Modifiable Risk Factors

Females suffer up to six times more NC-ACL injuries[32] and are twice as likely to develop PFP[33] than their male counterparts. They demonstrate greater maximum knee valgus angle and total knee valgus motion during dynamic activities, which is consistent with the MKD movement pattern. Hewett et al. has theorized that landing with the knee in a valgus position decreases joint stability, making the knee more susceptible to injury.[34] Ford et al. has suggested that this biomechanical alteration is one of the reasons why females suffer more NC-ACL injuries compared to males.[35]

The primary anatomical factors observed with respect to noncontact knee injury risk include knee-joint geometry, knee-joint laxity, body composition, and lower extremity structural alignment[36] (Table B-1). A majority of the anatomical variables that contribute to knee injury risk differ by sex,[36,37] suggesting that the risk factors may not be the same for males and females. A smaller femoral notch width has shown predictive ability for NC-ACL injury in both men and women.[27,36] Both increased general joint laxity,[38,39] and knee laxity[40] have been related to higher-risk landing strategies, more often identified in females. Additionally, greater BMI has been shown to predict ACL injury in females, and when combined with knee joint laxity, the risk for injury substantially increases.[36] Risk for injury in males is increased in those who exhibit excessive anterior-posterior knee displacement, posterior knee stiffness, navicular drop, and standing Q-angle.[37]

Risk factor (s)	All subjects	Men	Women
Body weight (1 SD ≥ mean)	1.9	1.2[a]	3.2
BMI (1 SD ≥ mean)	2.0	0.8[a]	3.5
Generalized joint laxity (≥ 5 regions)	2.8	3.1	2.7
Notch width (1 SD ≤ mean)	3.8	3.7	4.0
Laxity on KT-2000 arthrometer testing (134 N; 1 SD ≥ mean)	2.6	2.2[a]	2.7
Notch width + BMI	8.5	2.0	26.3
Notch width + generalized laxity	3.3	7.8	8.2
Notch width + KT-2000	6.4	2.0	16.8
BMI + generalized laxity	2.1	None injured	13.2
BMI + KT-2000	8.0	None injured	37.7
Notch width + BMI + generalized laxity	7.6	None injured	All injured
Notch width + BMI + KT-2000	21.3	None injured	All injured

[a] Risk factor was not significantly different when injured were compared with uninjured.

Table B-1. Relative Risk for ACL Injury Associated With Anatomical Risk Factors[36]

Modifiable Risk Factors

Several kinematic variables have been associated with noncontact knee injury (Figure B-2). In particular, ACL injury mechanisms typically include rapid knee valgus and internal rotation,[41] decreased knee flexion, a relatively extended knee,[42] increased lateral trunk motion,[43] and a more posteriorly positioned center of mass.[44] Risk for

overuse injuries, such as PFP, include an increase in knee valgus angle & moment, decreased knee flexion angle, and decreased trunk flexion.[45]

Motor recruitment strategies[7,46,47] and muscular strength imbalances[34,47-49] have been reported as contributing factors to the MKD movement during functional tasks. Imbalances in neuromuscular activation has been identified between the quadriceps and hamstrings,[34,47] which has been hypothesized to lead to increased knee valgus. Another theory identified weak or underactive hamstrings,[22] which leads to a decrease in quadriceps contribution, and thus an altered relationship. As a result of this decreased co-contraction, dynamic knee stiffness increases, as well as excessive frontal plane movement at the knee. Most frequently, focus has been placed on evaluating the relationship between hip abductor strength and knee valgus motion. The MKD strategy has traditionally been associated with deficits in strength, muscular imbalances and poor neuromuscular control of the hip and trunk,[46,48] however minimal correlation has been found between the strategy and the aforementioned deficits.[48,49]

Movement efficiency and functional mobility are qualitative expressions of the kinetic chain and are based on postural stability, strength, endurance and neuromuscular control.[50] One of the most common risk factors for noncontact knee injury is an increase in knee valgus motion during functional tasks.[22,35]

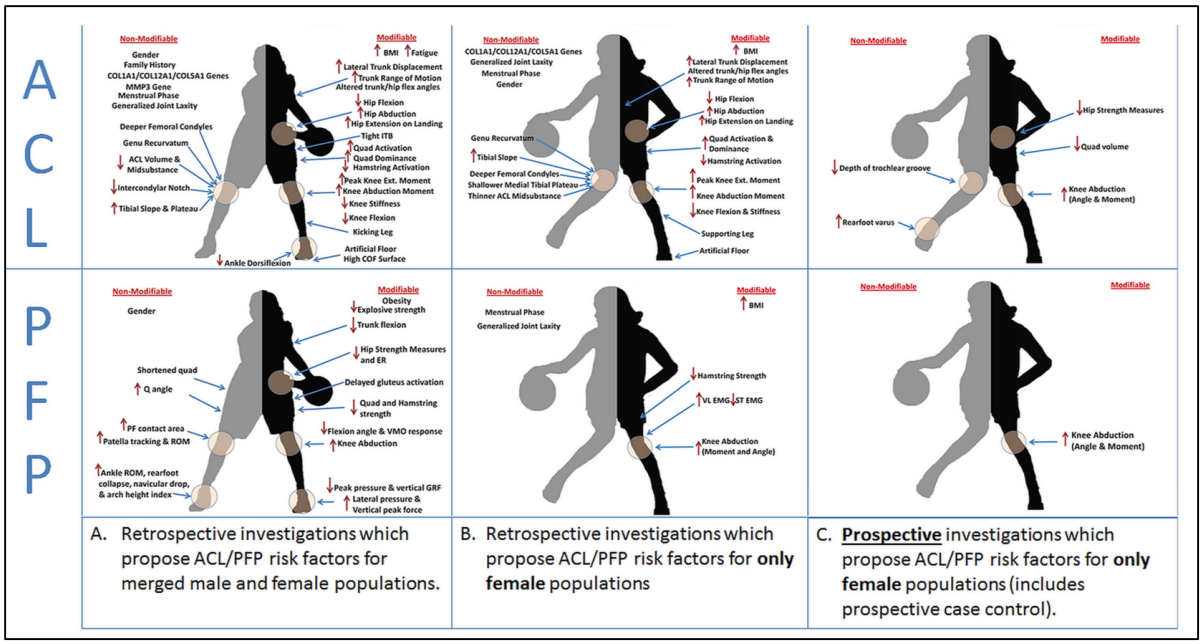


Figure B-1. Risk Factors for ACL Injury and PFP Incidence[45]

MEDIAL KNEE DISPLACEMENT

Poor alignment of the lower extremity during functional activities has been shown to increase the likelihood of sustaining a noncontact knee injury.[34,47,51] In particular, increased frontal plane motion at the knee has been discouraged during landing and plyometric tasks,[22,34] as it places increased stress on the mechanical restraints and stabilizing structures.[52] The dynamic knee valgus (DKV) movement pattern is defined as a strategy utilized during functional tasks that results in excessive knee valgus motion. In the clinical setting, DKV is often evaluated as the visual observation of medial knee displacement (MKD) by healthcare providers or sports science professionals.

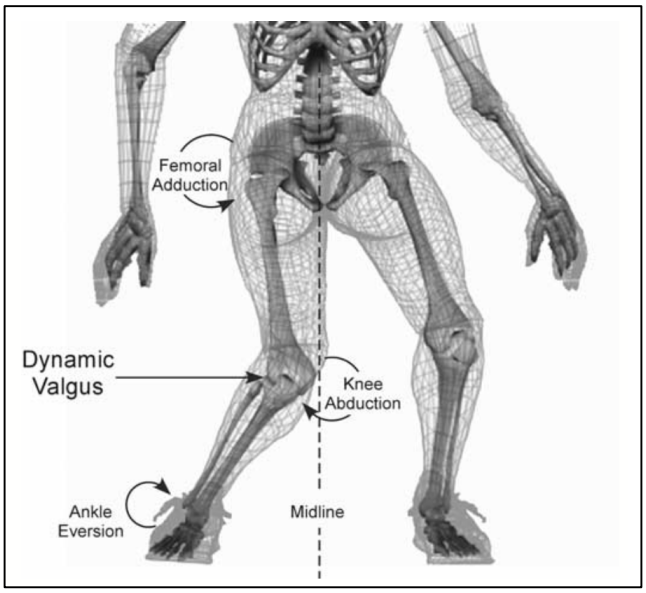


Figure B-2. Dynamic Knee Valgus Movement Pattern[22]

Researchers have associated excessive MKD during landing with ACL injury risk, and have utilized the strategy to prospectively identify those at risk for future injury.[12,22,35,53] Primary associations have been made between increases in lateral trunk flexion, hip internal rotation, knee valgus, ankle eversion, and a decrease in ankle dorsiflexion, during functional tasks. In order to effectively address neuromuscular issues pertinent to knee injury, quantification of the involved movements is necessary.

LOWER EXTREMITY SCREENINGS

The ability to assess abnormal movement patterns during a functional assessment has become increasingly important when screening for knee injury risk. Rather than observe solely activity-specific movement when determining risk, we must also evaluate functional health based on total movement quality and efficiency. Prior to implementing movement correction or injury prevention programs, effective screening methods for established noncontact knee injury risk factors should be utilized to identify aberrant movements.[54,55] Qualitative and quantitative visual assessments of individuals displaying

MKD have been described during functional tasks. While both three dimensional motion analysis (3DMA) and two dimensional (2D) video analysis have been deemed valid[48,56-58] and reliable[56,59,60] in the laboratory or research setting, many clinicians do not have access to the equipment necessary to utilize these methods. As a result, visual screenings have been developed to identify lower extremity risk factors without the need for technology or advanced equipment. Many of the screenings evaluate the same or comparable tasks as 3DMA assessments. In particular, several visual screenings evaluating frontal plane knee motion include drop vertical jump (DVJ),[12] the overhead squat (OHS),[23,24,61] and the single leg squat (SLS).[48,49,62,63].

The Landing Error Scoring System (LESS) has been validated as a screening tool utilized to identify lower extremity risk factors during the DVJ.[12] The assessment evaluates the drop vertical jump task for errors related to trunk, hip, knee, and ankle movement in the frontal and sagittal planes. In particular, the LESS has demonstrated predictive validity to identify noncontact ACL injuries in a population of youth athletes.[64] Similarly, the OHS test is a bilateral assessment of lower extremity kinematics.[65] However, contrary to the DVJ, the OHS is slower and perhaps easier for clinicians to evaluate in real-time than jumping tasks. This task has also demonstrated the ability to identify individuals displaying movement patterns at risk for injury.[23,24] Both the DVJ[12] and OHS[14,24] tasks utilize the visual observation of medial knee displacement (MKD) to represent knee valgus angle, and have been validated against the gold standard 3DMA.

The single leg squat (SLS) is a unilateral, foundational task that has been used to identify faulty lower extremity mechanics, particularly at the knee.[12,66] This task is able to visually reveal kinematic, proprioception and neuromuscular control deficits in either a

qualitative or quantitative manner, and without the utilization of technology or equipment. The SLS has traditionally been used to identify individuals with hip abductor strength deficits and poor trunk control,[46] although these identifications were primarily based on anecdotal evidence. Recently, Mauntel et al. determined that visual observation of MKD during the SLS did in fact correspond with the knee valgus angle measured by 3DMA,[67] but the researchers did not evaluate the utility of the assessment as a diagnostic test. Additionally, previous studies evaluating the SLS[48,49,62] have excluded individuals with a history of lower extremity injury, yet frontal plane deficits exist at the hip and knee in athletes up to 4 years following ACL reconstruction,[68] and it has been suggested that lower extremity injury is the greatest risk factor for future injury. These findings suggest that further research using the SLS task is warranted to aid in the identification of injury risk factors.

INJURY PREVENTION PROGRAMS

Injury prevention programs have been developed with the goal of correcting faulty lower extremity biomechanics to decrease the incidence of noncontact knee injuries. While a variety of intervention strategies have demonstrated reductions in knee injury risk, neuromuscular training has been the most successful in improving lower extremity mechanics.[69-71] Their success in decreasing injury risk [10,72-74] can be attributed to an emphasis placed on correct landing techniques[34,75] and increasing lower extremity strength[72,76] & proprioception.[22,77] Moreover, as compliance with the training program increases, incidence of injury decreases.[73]

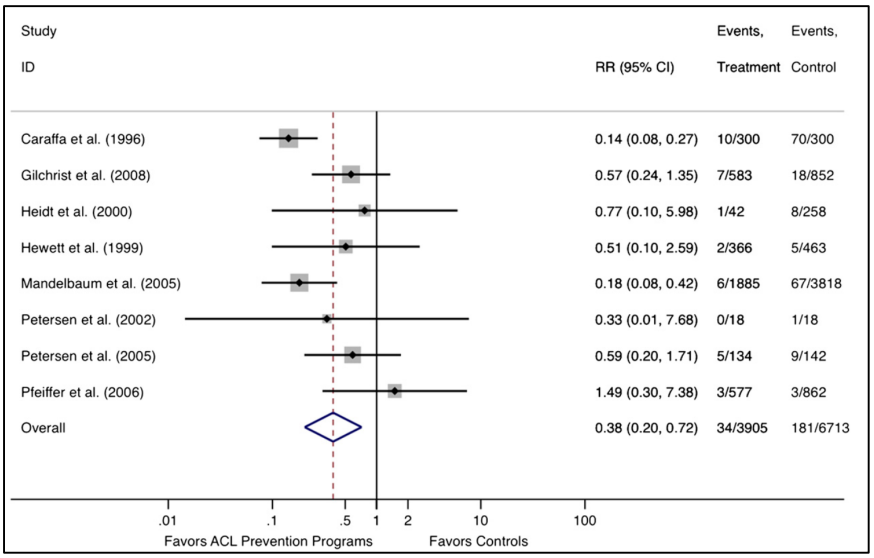


Figure B-3. Pooled Effect of ACL Prevention Programs[74]

Studies have primarily focused on implementation of the training program to large groups to evaluate its effectiveness, however recent research has indicated that individuals respond differently based on their preferred biomechanics.[10] Those designated as "high risk", based on frontal plane knee motion, have greater improvements in lower extremity biomechanics after completing a neuromuscular training program. However, these improvements are not great enough to re-categorize these individuals as "low risk".[10] This finding suggests that identifying individuals that display medial knee displacement (MKD) on visual screenings[12,78,79] may provide insight into who may be at a heightened risk and would benefit the most from intervention. Several lower extremity injuries, such as chronic ankle instability[80] and patellofemoral pain,[81] have shown success when utilizing an impairment-based rehabilitation program as compared to a traditional program which progresses individuals at a standardized rate. Utilizing lower extremity screenings to modify prevention programs to target "high risk" individuals with necessary corrections and strategies may improve outcomes and reduce risk of

noncontact knee injury to a greater degree. A meta-analysis on neuromuscular prevention programs[7] concluded that those including feedback and analysis of technique during functional tasks decreased ACL injury risk, whereas those that did not include feedback found no risk reduction.

FEEDBACK

Cognitive function has been cited as an integral component to the transfer of learned movement from a controlled to a more dynamic environment.[82] The utilization of feedback in training or rehabilitation sessions promotes problem solving and intrinsic learning, and is an effective method to enhance the learning of new movement patterns.[18,76,83]

Visual feedback has been implemented in either real-time (RTF) or post-response to target neuromuscular alterations. RTF provides individuals the opportunity to observe their movements and to make immediate biomechanical alterations, which may be an improvement on traditional post-response methods, where feedback is provided after the task is completed. Positive alterations to lower extremity kinematics have been demonstrated when RTF is implemented during both tuck jump[19,20] and jump-landing tasks,[84,85] however clinicians frequently prescribe corrective exercises that are slow, low intensity, and repetitive. There is little to support the ability of this treatment modality to alter the mechanics of tasks in which the participants are not trained.[16] Additionally, much of the evidence using RTF to improve mechanics associated with knee injury risk has evaluated outcomes using bilateral tasks.[15,16,19] Numerous athletic movements occur on a single leg (i.e. landing, cutting) suggesting that additional research is warranted in this area. Furthermore, researchers have evaluated this intervention in healthy

participants,[16,18,20,85] but have yet to establish its use in a population screened for kinematic risk factors.

In addition to kinematic feedback, RTF based on joint kinetics has also been utilized, however the results have been inconsistent. Beaulieu et al.[15] did not see any changes in landing mechanics after 2 sessions of RTF on knee abduction moment during the DVJ. In a pilot study, Ford et al.[16] compared kinematic and kinetic focused RTF provided during double leg squats, and found that the kinetic feedback was successful in improving both knee abduction moment and maximum knee valgus angle during the DVJ task. This was the first study that found improvements utilizing the concept of "skill transfer", where the participants trained different tasks in which they were tested. However, the researchers had a small sample size (n=4), and only evaluated peak biomechanical variables versus assessing throughout the entire task. The results of the present study were similar, albeit with a different form of RTF.

CONCLUSION

Individuals exhibiting aberrant lower extremity movement are at increased risk for noncontact knee injury. [12,22,77]The ability to perform mass field-based screenings with the use of observational tests would allow sports medicine professionals to intervene more effectively with corrective exercise, and promote athlete education regarding sport-specific, at-risk positions. Visual feedback has been demonstrated to improve lower extremity kinematics,[16,18] however it is unknown whether the same results would be observed when the concept of skill-transfer is implemented with a group exhibiting MKD.

APPENDIX C
Additional Methods

Table C-1. Overall Study Procedures

1. **Visit #1: Exercise & Sport Injury Lab**
    a. Informed Consent
    b. Review Eligibility Criteria
    c. Single Leg Squat Visual Test
    d. Motion Capture & sEMG Setup
    e. Motion Capture Single Leg Squat Trials
2. **Visit #2: Exercise & Sport Injury Lab – Gait Lab**
    a. Informed Consent
    b. Review Eligibility Criteria
    c. Randomization to Feedback or Active Control Group
    d. Single Leg Squat Visual Test
    e. Motion Capture Setup
    f. Baseline Single Leg Drop Vertical Jump Trials
    g. Exercise Progression
    h. Post-Intervention Single Leg Drop Vertical Jump Trials

Table C-2a. Informed Consent for Manuscripts I & II: Pages 1-4

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 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.

Participant's Name_____

Principal Investigator:	Susan Saliba Associate Professor, Human Services 203 Memorial Gymnasium P.O. box 400407 434-243-4033 saf8u@virginia.edu
Sponsor:	Mid-Atlantic Athletic Trainers' Association Accelerated Care Plus

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?

Mid-Atlantic Athletic Trainers' Association and Accelerated Care Plus

Why is this research being done?

The purpose of this study is to determine what strength, range of motion, movement during functional activities, muscle activity and patient reported outcomes look like in healthy individuals.

You are being asked to be in this study as a healthy individual. You will have your flexibility, strength, muscle function and movement of your hip, knees and ankles evaluated during many tasks. These tasks include squatting, stair climbing, walking, jogging, lunging, jumping, squatting and balancing.

Up to 86 people will be in this study at UVA, up to 40 people will be in this part of the study.

What will happen if you are in the study?

The test and all procedures are all being done for research purposes only.

VISIT 1a – CONSENT AND SCREENING (will take approximately 20 minutes to complete):
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 that it is safe for you to participate. These include completing questionnaires asking about

- o your knee pain (Anterior Knee Pain Scale)
- o current physical abilities and limitations (Activities of Daily Living Scale or ADLS, Lower Extremity Functional Scale or LEFS, and Short Form-12)
- o your activity level (Tegner activity scale and Godin Leisure Activity Scale)
- o if fear of pain limit your activity (Fear Avoidance Belief Questionnaire)
- o We will also review your Medical history and complete the Medical Questionnaire-Lower extremity form.

If these tests show you are eligible, you will be enrolled in the study.

VISIT 1 B – STUDY TEST AND PROCEDURES: (will last about 2 hours)
You have the option of continuing to complete Visit 1 B procedures below OR if it is not convenient, we will schedule a time for you to complete Visit 1B below. You should not have any medication for pain for 4 hours before this testing.

Warm up
- You will be provided 5-minutes to warm up on s stationary bike or treadmill.
- You will be provided 5-minutes to stretch any muscles you would like.

Range of Motions and Lower Extremity Alignment Measure:
- You will have your ankle and knee alignment measured. You will be asked to lay on a table in a comfortable position. Three measures will be recorded.
- You will have your ankle, knee and hip range of motion assessed 3 times in 6 directions. These motions will be pulling your toes towards your body, having your leg raised strength into the air, bending your knee as much as possible, having your hip raised and lowered, and rotating your leg outward.

Strength Measures using Electromyography
- You will have small sensors attached to your skin that will passively record how much your muscles turn on.

- You will strength will be assessed three time in 7 directions. These directions will be straightening or bending your back, knee, hip and ankle to make sure the sensors are over the correct places and are being recorded by the computer.

Functional Tasks using Electromagnetic Tracking System
- You will be attached with sensors placed on the skin, to a tracking system that will help us look at how you move during the "functional tasks" (see below).
- You will perform 7 functional tasks as described below:
  - o You will be asked to stand on your bad leg and bend your knee to lower yourself as low to the ground as possible and then return back to the starting position. You will do this 4 more times (5 total)
  - o You will stand on a small step, and will reach down as if taking a step down a stair. Once your heel touches the ground you will return to the starting position with both legs on the step. You will repeat this 5 times total
  - o You will go up and down two steps continuously. You will repeat this 5 times total.
  - o You will complete a lunge task, where you bring one leg out in front of you and lower your body to the ground and then return to the starting position. You will repeat this 5 times total.
  - o You will walk and jog on a treadmill for 5 minutes each.
  - o You will complete a jumping task from a box that is one foot tall. You will jump off the box onto the ground, and then jump straight into the air as high as possible. You will repeat this 3 times.
  - o You will balance on force plate on your bad limb (eyes open and eyes closed) for ten seconds.

Ultrasound Imaging
- You will have up to 12 images of your stomach and 12 images of your outside hip recorded with a real-time ultrasound machine to measure your muscles around your stomach.
  - o You will be asked to be on your side with knees bent with a bolster resting under knees.
  - o The ultrasound gel will be placed directly on the skin.
  - o The head of the ultrasound wand (called a transducer) will be moved around your abdomen to take images.
  - o You will be asked exhale and then draw your navel up and towards their spine several times while images are taken.
  - o This procedure will be repeated for the opposite side
  - o You will then stand with feet shoulder width apart and hands to your sides. You will be asked to exhale and then draw your navel up and towards your spine several times while images are taken.
  - o You will then lay on your side with your knee straight.
  - o The ultrasound gel will be placed directly on the skin.
  - o The head of the ultrasound wand (called a transducer) will be moved around your outside hip to take images of the hip muscles.
  - o You will then raise your leg into the air and additional images will be taken
  - o The procedures will be repeated for the opposite side

Core Endurance Test

- You will have your core strength measured by timing how long you can hold a plank. A plank is where you use your feet and arms to hold yourself off the ground and keep your body in a straight line. You will have this timed with a stopwatch. You will also repeat this on each side.

Visual Analog Pain Scale:
- This is a 10 point scale we will ask you to complete at different times during the testing above and after each rehabilitation session described below.

Pedometer Assessment:
- You will be given a pedometer (FitBit) to wear on your wrist for 2-weeks. Following the 2-week you will turn it back over to the research team.

What are your/your parent/legal guardian's responsibilities in the study?

You and your parent/legal guardian have certain responsibilities to help ensure your safety. These responsibilities are listed below:

- If you are under 18 years of age, your parent/legal guardian must bring you to each study visit.
- You and your parent/legal guardian must be completely truthful about your health history.
- Follow all instructions given.
- You or your parent/legal guardian should tell the study doctor or study staff about any changes in your health or the way you feel.
- Answer all of the study related questions completely.
- Inform the study doctor or study staff as soon as possible if you have to take any new medications, including anything prescribed by a doctor or those that you can buy without a prescription (over-the-counter), including herbal supplements and vitamins. The study doctor will let you know if you can take these medications.
- Do not take any pain medications 4 hours prior to each session. You many resume pain medications once the sessions are completed

How long will this study take?

Your participation in this study will require up to 2- testing visits (we can split these as needed). You will also need to come back to the laboratory in 2-weeks to return the pedometer (FitBit).

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 to the study include:

Likely

Table C-2b. Informed Consent for Manuscripts I & II: Pages 5-8

- Possible mild, temporary skin irritation from electrodes.

Less Likely

- Possible mild muscle strain or soreness from testing
- Possible joint discomfort/mild pain after testing
- Possible discomfort during administration of the electrical stimulation (Some people may have hypersensitivity to an electrical stimulus. If you are having any pain or strong discomfort when the stimulus is being applied please let the researcher know immediately.)

Risks and side effects of drop jump task:

- Muscle soreness during or after testing
- Discomfort in the joints of the lower extremity during or after testing
- Potential for knee or ankle injury

Risk for women

Physical therapy programs may or may not pose risk for pregnant women/unborn child depending on the health of the mother. Additionally the effect of electrical stimulation delivered as part of this study is not known in pregnant women or in unborn babies. Therefore, we will not enroll pregnant women in this study or allow anyone who becomes pregnant to remain in the study.

Other unexpected risks:

You may have side effects that we do not expect or know to watch for now. Call the study leader if you have any symptoms or problems.

Could you be helped by being in this study?

You may benefit from being in this study as the therapeutic exercises provided over the 4-weeks of rehabilitation should improve strength and decrease pain.

What are your other choices if you do not join this study?

You do not have to be in this study for to receive physical therapy using electrical stimulation. Your doctor can prescribe physical therapy and you may receive that therapy wherever you wish. Physical therapy may include various kinds of electrical stimulation.

Will you be paid for being in this study?

You will not receive compensation for completion in this.

Will being in this study cost you any money?

Being in this study will not cost you any money. There is no cost to you or your health insurance for the procedures/tests, which are being done for research purposes. Specifically, the study provides 4 weeks of physical therapy at no cost to you or your 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. 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 can take you out of the study. Some of the reasons for doing so may include

a) The Principal Investigator is concerned about your health due to increase pain while performing the functional tasks.
b) Pregnancy.
c) The principal investigator, or the IRB decides to stop the study earlier than anticipated.

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. This may include mental health care records, substance abuse records, and/or HIV/AIDS records.

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.

A description of this clinical trial will be available on *http:// www.ClinicalTrials.gov*, as required by U.S. Law. This Web site will not include information that can identify you. At most, the Web site will include a summary of the results. You can search this Web site at any time.

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 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

Principal Investigator: Susan Saliba
Human Services, Curry School of Education
Saf8u@virginia.edu
Telephone: (434)243-4033

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

PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

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

Person Obtaining Consent from Adult Participant

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

Parental/ Guardian Permission

By signing below you confirm you have the legal authority to sign for this child.

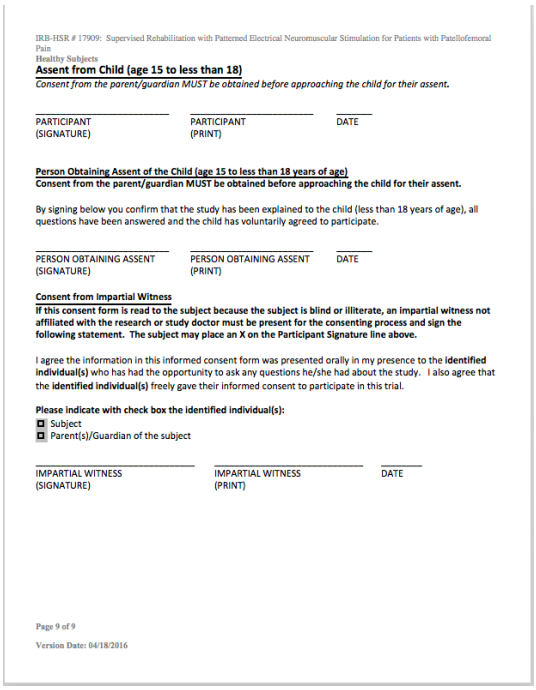
PARENT/GUARDIAN (SIGNATURE)	PARENT/GUARDIAN (PRINT NAME)	DATE

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

Table C-2c. Informed Consent for Manuscripts I & II: Page 9



Assent from Child (age 15 to less than 18)

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 (age 15 to less than 18 years of age)
Consent from the parent/guardian MUST be obtained before approaching the child for their assent.

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

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.

Please indicate with check box the identified individual(s):

- ☐ Subject
- ☐ Parent(s)/Guardian of the subject

_____	_____	_____
IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Table C-3a. Informed Consent for Manuscript III: Pages 1-4

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 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.

Participant's Name_____

Principal Investigator:	Susan Saliba, Ph.D, M.P.T., ATC Department of Kinesiology PO Box 400407 Charlottesville, VA 22908 (P) 434-243-4033 (E) saf8u@virginia.edu
Sponsor:	Curry School of Education

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?

Curry School of Education

Why is this research being done?

The first purpose of this study is to compare the difference between two different tools that measure lower body joint angles, the Vicon motion capture system and the Microsoft Kinect, while performing different tasks or lower body movements.

The second purpose of this study is to look at individuals whose knee moves to the inside of their leg during a single leg squat. Half of the individuals will perform exercises, and the other half will perform exercises with a TV that shows the way your knee is moving. Both groups will then be asked to do the same jumps off of a small box to see how they move.

You are being asked to be in this study, because you are a healthy individual. Up to 75 people will be in this study at UVA.

What will happen if you are in the study?

SCREENING

Screening & Consent (Will take about 10 minutes to complete):
If you agree to be in this study, 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 to make sure you are eligible and it is safe for you to participate. These include the following:

- Review of your medical history
- Height and weight measurement

If these items show you are eligible, you may continue with the study today, or you may return another day to complete the study procedures.

STUDY PROCEDURES

Questionnaires (Will take about 5 minutes to complete):
If you are eligible and agree to participate, you will be asked to fill out some questionnaires. These questionnaires ask about:

- Your general medical history *(EASIL Medical Questionnaire: Lower Extremity)*
- Your physical activity level *(Godin Time-Leisure Exercise Questionnaire, Tegner Activity Scale)*
- Your knee pain *(Visual Analog Scale)*

Single Leg Squat Test (Will take about 5 minutes to complete):
You will perform a single leg squat with your arms across your chest, and opposite leg bent behind you. You will lower yourself down to a comfortable depth and stand back up while the researcher watches your knee.

PART A (Will take about 50 minutes to complete):
Functional Tasks

You will be attached to a motion capture system with sensors taped on the skin that will help us look at how you move, and at the same time the Microsoft Kinect will track your movement through a video camera. You will be asked to perform several different "functional tasks" (see below) while the two systems observe your movement:

- You will be asked to bend your knees to lower yourself as low to the ground as possible, and then return back to the starting position. You will do this 4 more times (5 total).
- You will be asked to stand on one leg, bend your knee to lower yourself as low to the ground as possible, and then return to the starting position. You will complete this 5 times total on each leg.
- You will stand on a small step, and will reach down as if taking a step down a stair. Once your heel touches the ground you will return to the starting position with both legs on the step. You will complete this 5 times total on each leg.
- You will stand on a small step, and will reach down as if taking a sideways step down a stair. Once your heel touches the ground you will return to the starting position with both legs on the step. You will complete this 5 times total on each leg.
- You will complete a lunge task, where you bring one leg out in front of you and lower your body to the ground and then return to the starting position. You will complete this 5 times total on each leg.
- You will walk up and down two steps at your own pace. You will complete this 3 times.
- You will complete a jumping task from a box that is one foot tall. You will drop from the box and then jump straight into the air as high as possible. You will complete this 5 times total.
- You will be asked to stand on one leg on top of a box that is one-foot high, and then drop onto a platform, landing on the same leg that you started on. You will complete this 5 times total on each leg.

You will be videotaped while performing the tasks and you may rest between each task as needed. Once you have finished the movement tasks, your participation is this study is complete.

PART B (Will take about 40 minutes to complete):
If your knee moves to the inside of your leg during the single leg squat, you will be randomly assigned (like the flip of a coin) to one of two groups:

Group 1: Exercise Group 2: Exercise + Feedback.

Both groups will complete the same exercises. The group that has the feedback will see a TV that shows their knee movement during the different exercises.

- You will be asked to bend your knees to lower yourself as low to the ground as possible, and then return back to the starting position. You will do this 9 more times (10 total).

- You will be asked to stand on one leg, bend your knee to lower yourself as low to the ground as possible, and then return to the starting position. You will complete this 10 times total.
- You will stand on a small step, and will reach down as if taking a sideways step down a stair. Once your heel touches the ground you will return to the starting position with both legs on the step. You will complete this 10 times total.

Both groups will then complete 5 jumping tasks off of a one-foot box. Each person will drop from the box and jump straight into the air as high as possible.

What are your and your parent/legal guardian's responsibilities in this study?

You and your parent/legal guardian have certain responsibilities to help ensure your safety.

These responsibilities are listed below:

- If you are under 18 years of age, your parent/legal guardian must bring you to the study visit.
- You and your parent/legal guardian must be completely truthful about your health history.
- Follow all instructions given.
- You or your parent/legal guardian should tell the study staff about any changes in your health or the way you feel.
- Answer all of the study related questions completely.

How long will this study take?

Your participation in this study will require 1 study visit. The visit will be between 90 minutes and 2 hours.

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?

Less Likely

- You may experience physical fatigue or mild joint/muscle discomfort during or after the exercises.

Table C-3b. Informed Consent for Manuscript III: Pages 5-8

- You may fall while performing the exercises which could result in an injury to the muscles, bone or ligaments of the foot.
- There is a small risk that a breach of privacy or confidentiality may occur, although this risk is minimal due to the privacy plan that is in place for this protocol.

Risks of Videotaping/Audio taping:

- You will be videotaped during the functional tasks in order to calculate values needed for comparisons.
- Your face will be shown.
- The tapes will be immediately uploaded onto a secure department server. Files will be saved using non-identifiable subject numbers.
- Videos will be deleted at the conclusion of analysis.

Other unexpected risks:
You may have side effects that we do not expect or know to watch for now. Call the study leader if you have any symptoms or problems.

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. If you are a patient at UVa your usual care will not be affected if you decide not to participate in this study. If you are an employee of UVa your job will not be affected if you decide not to participate in this study.

Will you be paid for being in this study?
If you are tested positive for dynamic knee valgus (if your knee moves inside your leg during a single leg squat) and complete Parts A & B of the study: you will be paid $30.

You should get your payment about 2-4 weeks after finishing the study. The income may be reported to the IRS 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 for 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. 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 can take you out of the study. Some of the reasons for doing so may include

a) You become injured and can no longer participate in the study
b) The principal investigator closes the study for safety, administrative or other reasons

If you decide to stop being in the study, we will ask you to verbally indicate that you are no longer interested in participating in the study to a member of the study team. If you do withdraw, a note will be placed in your file indicating that you withdrew from 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
- Your health information if required for this study.

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

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 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

Susan Saliba, Ph.D, M.P.T., ATC
Department of Kinesiology
PO Box 400407
Charlottesville, VA 22908
(P) 434-243-4033
(E) saf8u@virginia.edu

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

PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

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

Person Obtaining Consent From Adult Participant
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

Assent from Child Participant (age 15 to <18)
Consent from the parent/guardian MUST be obtained before approaching the child for their assent.

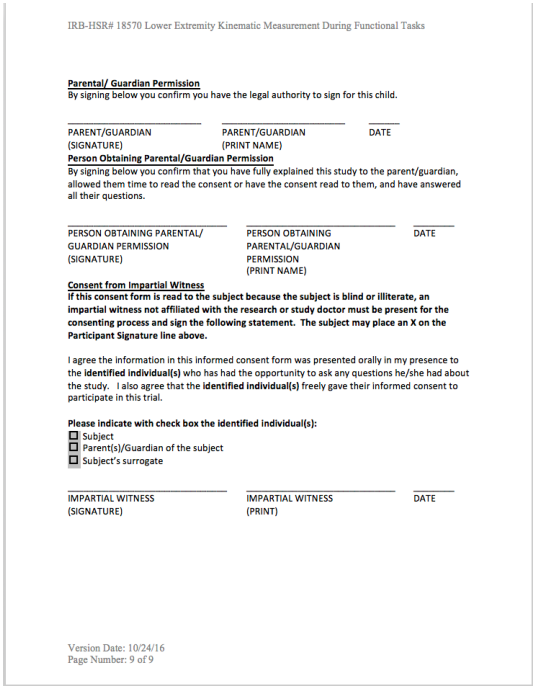
PARTICIPANT (SIGNATURE)	PARTICIPANT (PRINT)	DATE

Person Obtaining Assent of the Child Participant (age 15 to <18)
Consent from the parent/guardian MUST be obtained before approaching the child for their assent.

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

Table C-3c. Informed Consent for Manuscript III: Page 9



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

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 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.

Please indicate with check box the identified individual(s):
☐ Subject
☐ Parent(s)/Guardian of the subject
☐ Subject's surrogate

IMPARTIAL WITNESS (SIGNATURE)	IMPARTIAL WITNESS (PRINT)	DATE

Table C-4. Motion Capture Methods

1. **Equipment**
    a. Vicon Bonita Cameras (12) (Vicon Motion Systems, Oxford, UK)
    b. Vicon Nexus software (Vicon Motion Systems, Oxford, UK)
    c. Motion Monitor® software (version 9, Innovative Sports Training, Inc., Chicago, IL, USA)
2. **Vicon Nexus**
    a. Set frame rate to 250 Hz
    b. Masked and aimed cameras
    c. Calibrated cameras using 2500 refinement frames
    d. Set volume origin
3. **Marker Setup**
    a. Using elastic tape, secured eight marker clusters (four markers each affixed on semi-rigid thermoplastic plates)
        i. Right dorsum of foot, left dorsum of foot, right lateral shank, left lateral shank, right lateral thigh, left lateral thigh, sacrum and thoracic spine
4. **Motion Monitor Setup**
    a. Opened preference file, "17909_Functional Tasks"
    b. Confirmed markers
        i. Administration | Edit Sensor Parameters
        ii. Selected "Vicon Tracker"
        iii. Confirmed number of markers (36) and measurement rate (250 Hz)
        iv. Confirmed that all markers were recognized
        v. Confirmed that clusters were assigned to appropriate virtual sensors
            - Virtual Sensor 1: UpperBack1, UpperBack2, UpperBack3, UpperBack4
            - Virtual Sensor 2: Bottom_SC, Top_SC, ShortLat_SC, LongLat_SC
            - Virtual Sensor 3: LThigh1, LThigh2, LThigh3, LThigh4
            - Virtual Sensor 4: LShank1, LShank2, LShank3, LShank4
            - Virtual Sensor 5: LFoot1, LFoot2, LFoot3, LFoot4
            - Virtual Sensor 6: RThigh1, RThigh2, RThigh3, RThigh4
            - Virtual Sensor 7: RShank1, RShank2, RShank3, RShank4
            - Virtual Sensor 8: RFoot1, RFoot2, RFoot3, RFoot4
            - Virtual Sensor 9: Bottom, Top, LongLat, ShortLat
    c. Confirmed virtual sensor assignment
        i. Administration | Edit Sensor Assignments
            - Sensor 1: Thorax
            - Sensor 2: Sacrum
            - Sensor 3: Left Thigh
            - Sensor 4: Left Shank
            - Sensor 5: Left Foot

- Sensor 6: Right Thigh
- Sensor 7: Right Shank
- Sensor 8: Right Foot
- Sensor 9: Moveable (Stylus)

d. Setup virtual sensors
    i. Setup | Setup Virtual Sensors
e. Setup stylus
    i. Setup | Setup Stylus
    ii. Setup a new stylus with 10 readings, and calibrate stylus
f. Calibrate force plates
    i. Removed all weight from the forceplates
    ii. Zeroed forceplates in the hardware
    iii. Administration | Edit Force Plates | Configure | Calibrate (0 & 1)
    iv. Setup | Setup Forceplates
    v. Pressed stylus into the forceplate at three nonlinear locations
g. Setup subject sensors
    i. Setup | Setup Subject Sensors
    ii. Selected "Setup sensors using digitization"
    iii. Captured participant's body mass with participant standing on one forceplate
    iv. Captured participant's height by placing tip of stylus on participant's head
    v. Held stylus still to don sensors
    vi. Pointed out bony landmarks to digitize participant:
        - Left ASIS
        - Right ASIS
        - C7-T1
        - T12-L1
        - L5-S1
        - Left Lateral Knee Joint Line
        - Left Medial Knee Joint Line
        - Left Lateral Malleolus
        - Left Medial Malleolus
        - Tip of Left 2nd Phalanx
        - Right Lateral Knee Joint Line
        - Right Medial Knee Joint Line
        - Right Lateral Malleolus
        - Right Medial Malleolus
        - Tip of Right 2nd Phalanx

5. Data Collection

a. Collect functional tasks
    i. Single Leg Squat
    ii. Single Leg Drop Vertical Jump

Table C-5. Surface Electromyography Methods

1. **Instruments**
    a. Trigno™ wireless surface electromyography system (Delsys, Inc., Boston, MA, USA)
    b. Trigno™ Standard Sensors (12) (Delsys, Inc., Boston, MA, USA)
    c. Trigno™ Control Utility software (Delsys, Inc., Boston, MA, USA)
    d. Motion Monitor® software (version 9, Innovative Sports Training, Inc., Chicago, IL, USA)
2. **Surface Electromyography Setup**
    a. Double-sided adhesive Trigno™ skin interfaces (SC-F03) were affixed to 12 electrode sensors
    b. Electrodes were turned on (green light illuminates)
    c. Skin preparation: The area was shaved with a disposable razor, debrided with abrasive pad, and cleaned with isopropyl alcohol
    d. Electrodes were placed according to SENIAM guidelines (www.seniam.org)
3. **Electrode Placement**
    a. Paraspinal (Longissimus)
        i. Placed in the short-seated position
        ii. Location identified two finger widths lateral from L1 spinous process
        iii. Electrode oriented in the vertical direction
    b. Gluteus Maximus
        i. Electrode placed in the prone position
        ii. Location identified 1/2 the distance between the sacral vertebrae and greater trochanter; Palpation of the muscle belly was confirmed with manual resistance during hip extension
        iii. Electrode oriented in direction of line between the PSIS and the middle of the posterior portion of the thigh
    c. Gluteus Medius
        i. Electrode placed in the side-lying position
        ii. Location identified 1/2 the distance between the iliac crest and the greater trochanter; Palpation of the muscle belly was confirmed with manual resistance during hip abduction with slight extension & external rotation
        iii. Electrode oriented in the direction of the line between the iliac crest and the greater trochanter
    d. Adductor Longus
        i. Electrode placed in the short-seated position
        ii. Location identified 1/3 the distance between the pubic symphysis and the adductor tubercle; Palpation of the muscle belly confirmed with manual resistance during hip adduction
        iii. Electrode oriented in the direction of the pubic symphysis
    e. Biceps Femoris
        i. Electrode placed in the prone position

ii. Location identified 1/2 the distance between the ischial tuberosity and the lateral epicondyle of the tibia
iii. Electrode oriented in the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia

f. Vastus Lateralis
i. Electrode placed in the short-seated position
ii. Location identified 2/3 the distance between the ASIS to the lateral side of the patella; Palpation of the muscle belly was confirmed with manual resistance during knee extension
iii. Electrode oriented in the direction of the muscle fibers

g. Vastus Medialis Obliquus
i. Electrode placed in the short-seated position
ii. Location identified over the most prominent muscle belly – approximately 5cm superior and 3cm medial to the patella; Palpation of the muscle belly confirmed with manual resistance during knee extension
iii. Electrode oriented in 35º of medial rotation, in the direction of the muscle fibers

h. Medial Gastrocnemius
i. Electrode placed in the prone position
ii. Location identified as the most prominent bulge of the muscle; Palpation of the muscle belly was confirmed with manual resistance during plantarflexion
iii. Electrode oriented in the direction of the muscle fibers

4. Data Collection

a. Trigno™ Control Utility window was opened
b. Verified that each electrode utilized for collection was paired, and had adequate signal and battery life
c. Affixed double-sided adhesive Trigno™ skin interfaces (SC-F03) to 12 sensors
d. Electrodes were turned on (green light illuminated)
e. Maximal voluntary isometric contractions for the gluteus maximus and gluteus medius were collected in the prone and side-lying positions, respectively, after electrode placement
f. A 10-second quiet standing trial was collected with the participant standing with the feet shoulder width apart, and remaining as still as possible
g. Surface electromyography data was collected while participants completed single leg squat trials
h. Data was integrated with Motion Monitor® software

Table C-6. Isometric Strength Measurements

1. **Instruments**
    a. Handheld Dynamometer (Accelerated Care Plus Corporation, Reno, NV, USA)
2. **Data Collection**
    a. Participant instructed to push as hard as possible into the handheld dynamometer for 5 seconds
    b. Researcher provided enough resistance to maintain an isometric contraction
    c. Three trials collected for each motion:
        i. Hip Abduction
            - Participant positioned in side-lying position, with 20º of hip abduction, slight extension and external rotation
            - Handheld dynamometer placed on the lateral surface of the upper leg, 5cm proximal to the knee joint line
        ii. Hip Adduction
            - Participant positioned in a short-seated position with knee flexed to 90°
            - Handheld dynamometer placed on the medial surface of the upper leg, 5cm proximal to the knee joint line

Table C-7. Functional Task Methods

1. **Single Leg Squat**
    a. Participant setup
        i. Arms folded across chest
        ii. Single limb stance on limb of interest
    b. Participant instructions
        i. Two-second descent as far as comfortably possible
        ii. Two-second ascent back to single limb stance
        iii. Return to double limb stance
    c. Three practice trials were allowed
    d. Three test trials were collected with 1-minute rest between each trial.
2. **Single Leg Drop Vertical Jump**
    a. Participant setup
        i. Stood on 15cm box placed behind forceplate with toes at the anterior edge of the box
        ii. Transferred weight to limb of interest
    b. Participant instructions
        i. Drop off of box on single limb
        ii. Landing and complete maximum vertical jump
    c. Three practice trials were allowed
    d. Three test trials were collected with 1-minute rest between each trial

Table C-8. Exercise Progression Methods

1. **Three practice trials of each task were allowed before start of progression**
    a. Double leg squat
        i. Participant setup
            - Arms folded across chest
            - Double limb stance, with feet shoulder width apart
        ii. Participant instructions
            - Controlled descent as far as comfortably possible
            - Controlled ascent back to starting position
    b. Single leg squat
        i. Participant setup
            - Arms folded across chest
            - Single limb stance on limb of interest
        ii. Participant instructions
            - Controlled descent as far as comfortably possible
            - Controlled ascent back to starting position
    c. Single leg stepdown
        i. Participant setup
            - Hands on hips
            - Single limb stance on limb of interest on 15cm box
            - Toes at anterior edge of the box
        ii. Participant instructions
            - Lowered body until contralateral heel lightly touches ground, just anterior of box
            - Controlled ascent to starting position
    d. Lateral stepdown
        i. Participant setup
            - Hands on hips
            - Single limb stance on limb of interest on 15cm box
            - Foot placement on lateral edge of box
        ii. Participant instructions
            - Lowered body until contralateral heel lightly touches ground, just lateral to box
            - Controlled ascent to starting position
2. **Ten repetitions of each task were completed in order, with rest between tasks taken as needed**

Table C-9. Visual Feedback Methods

1. **Instruments**
    a. Microsoft Kinect™ (v.2, Microsoft Corp, Redmond, WA, USA)
    b. VirtualCoach software (Kinetech Labs, Charlottesville, VA, USA)
    c. PC Computer
2. **Kinect™ Feedback System Setup**
    a. Open VirtualCoach Software
    b. Select "Feedback" Group
    c. Input new participant information
    d. Select "New Session"
    e. Input session information
3. **Participant Positioning**
    a. Calibration
        i. Participant stands in anatomical neutral in front of Kinect camera so that head through feet can be captured
        ii. Adjust camera or participant as necessary to ensure that he or she is in the field of view
    b. Feedback
        i. Click "Record"
        ii. Exercise tasks are performed at the same distance from the Kinect camera as Calibration
        iii. Re-calibrate if joints are obstructed during exercises and feedback is altered

APPENDIX D
Additional Results

Figure D-1. Time Main Effect for Ankle and Knee Kinematic Excursions Pre-Post Intervention

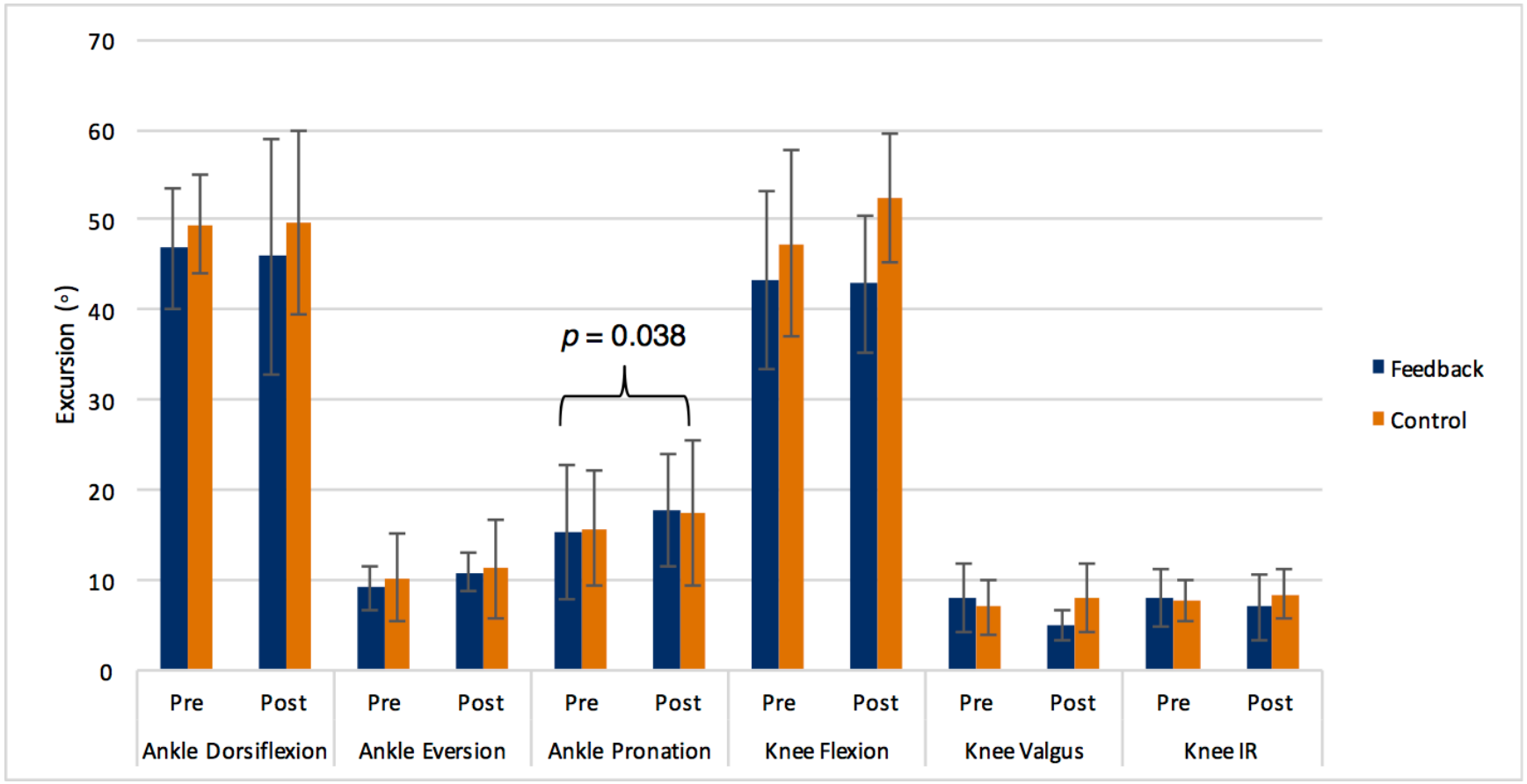


Figure D-2. Time Main Effect for Hip and Trunk Kinematic Excursions Pre-Post Intervention

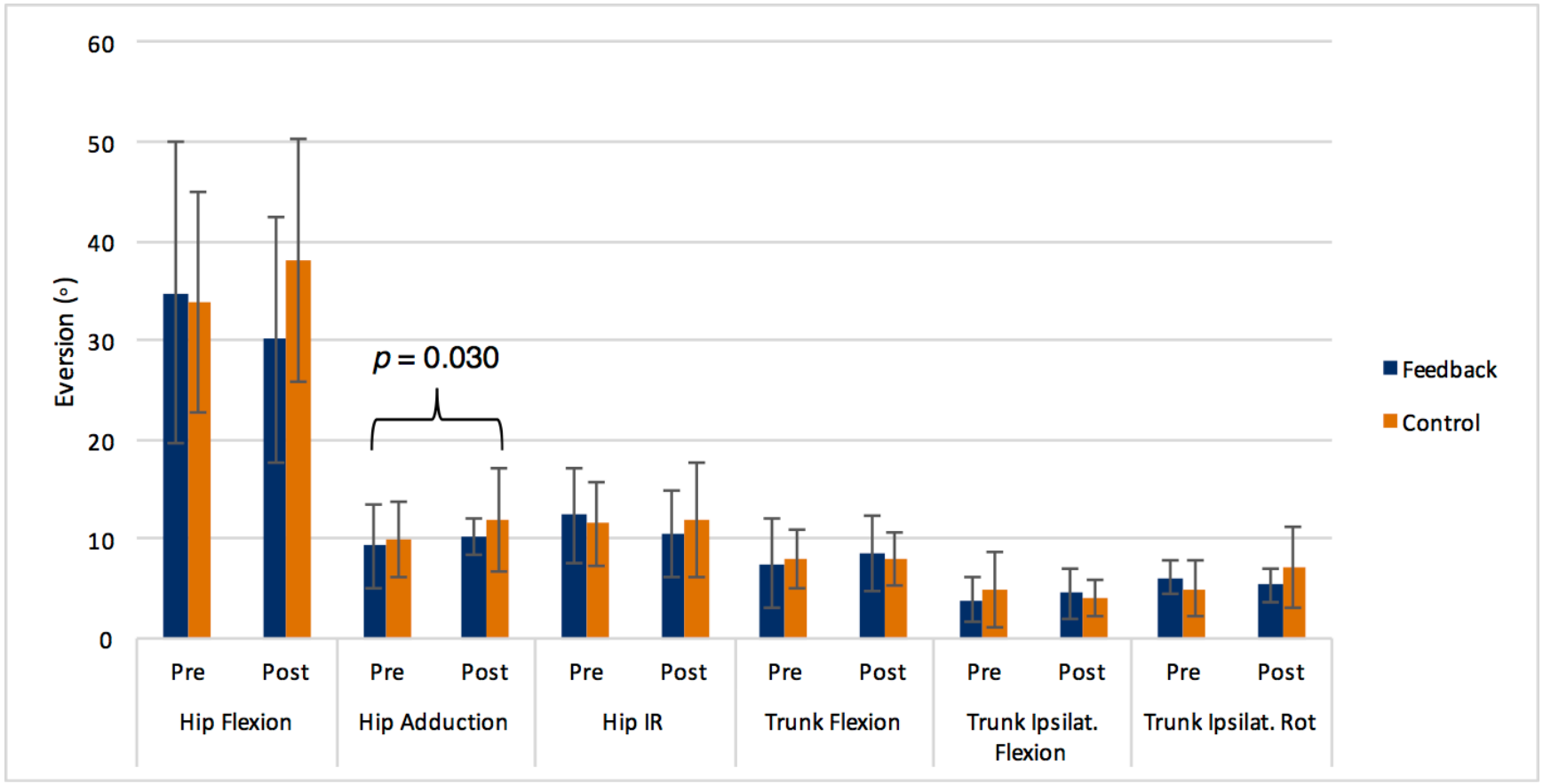


Figure D-3. Group Main Effect for Ankle and Knee Kinematic Excursions Pre-Post Intervention

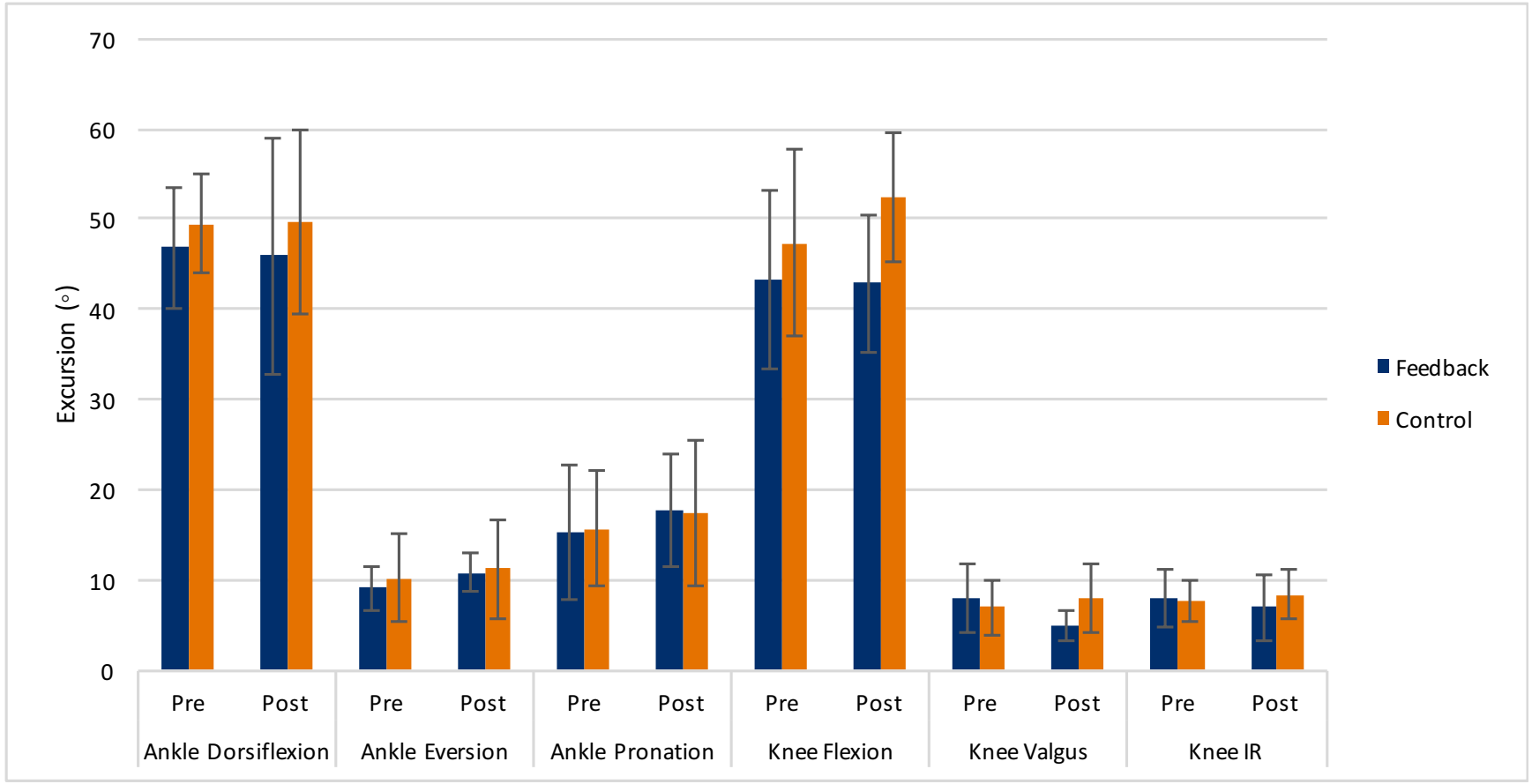


Figure D-4. Mixed Model ANOVA Results: Group Main Effect for Hip and Trunk Kinematic Excursions Pre-Post Intervention

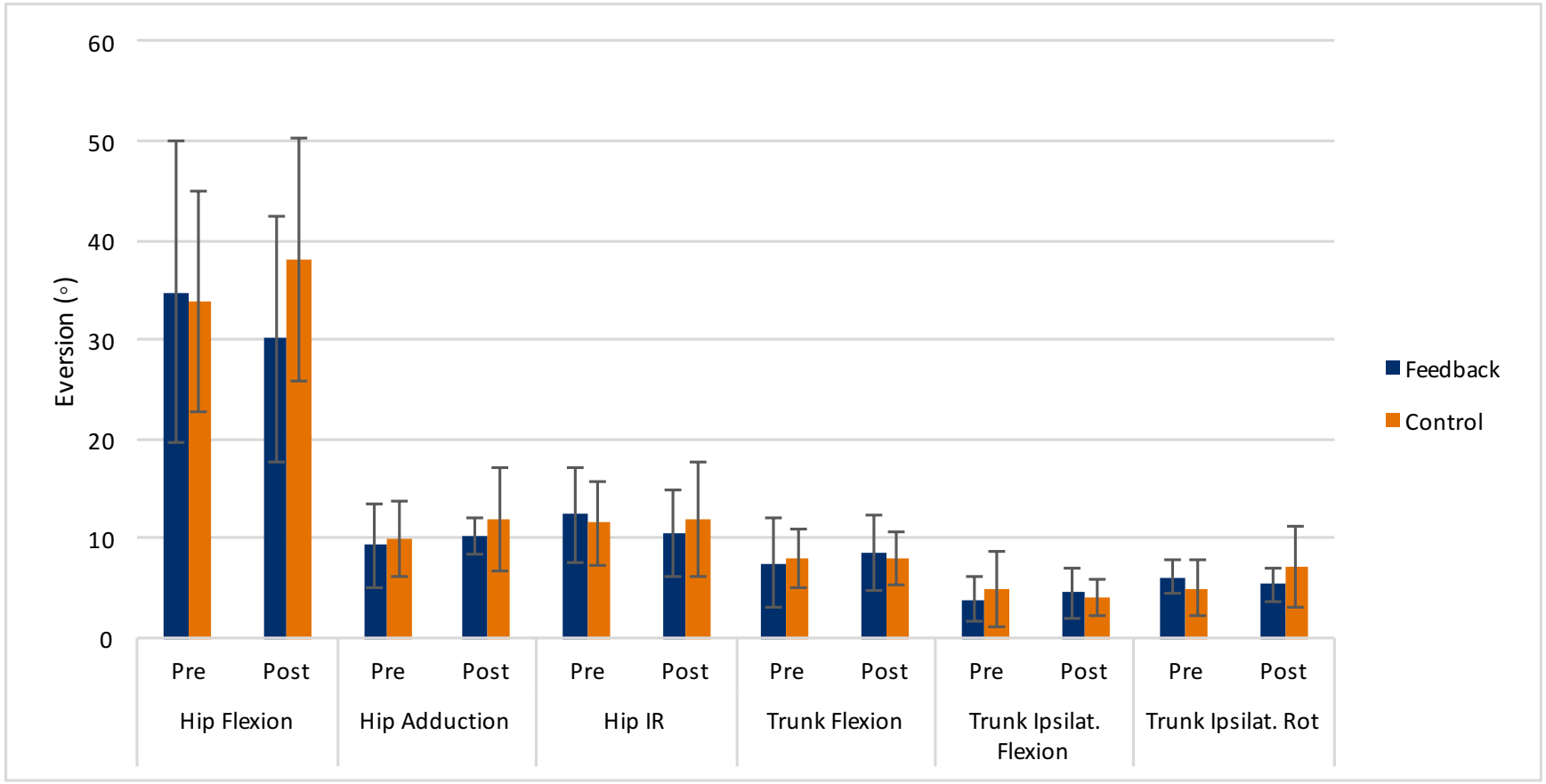


Figure D-5. Group x Time Interaction for Ankle and Knee Kinematic Excursions Pre-Post Intervention

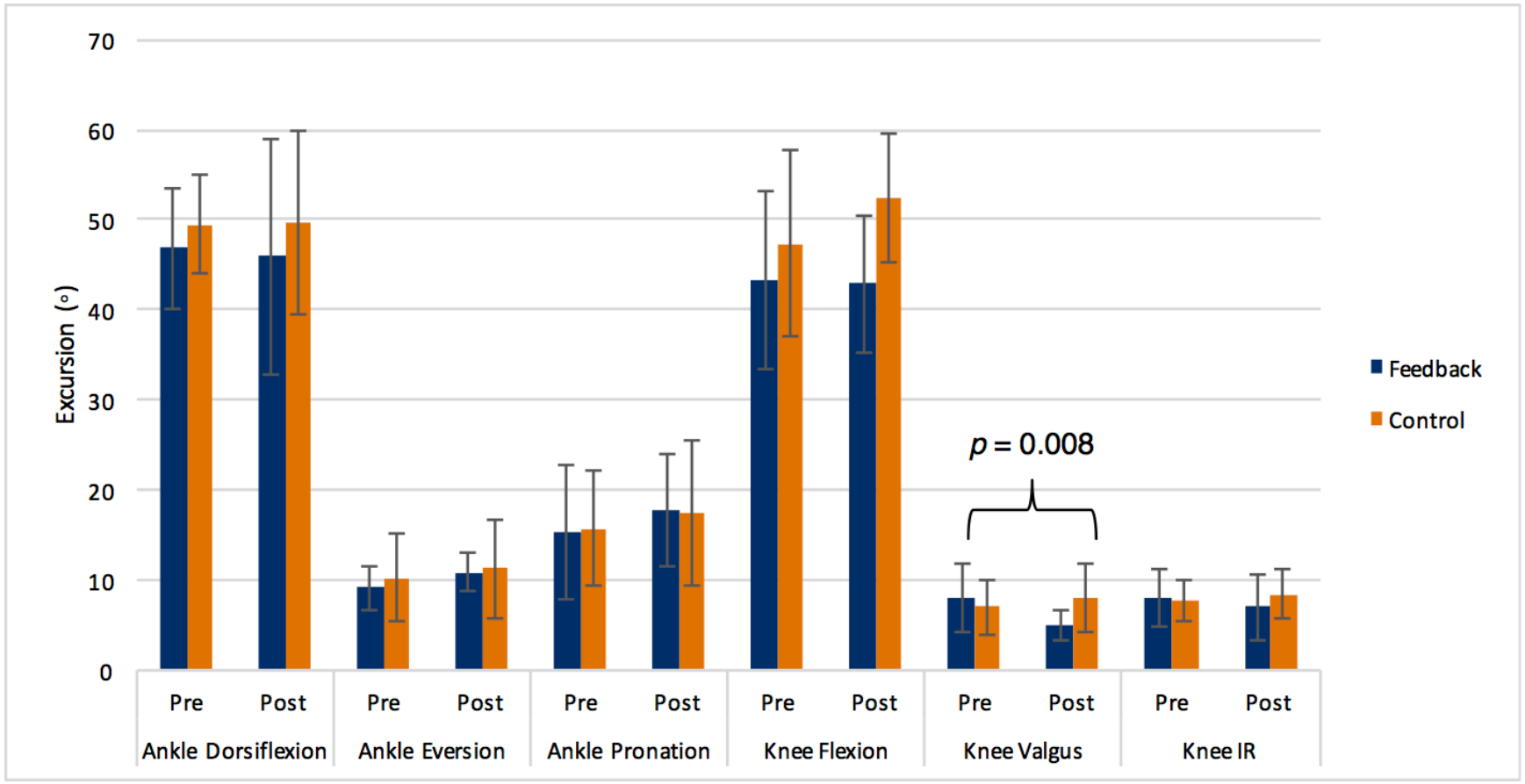


Figure D-6. Group x Time Interaction for Hip and Trunk Kinematic Excursions Pre-Post Intervention

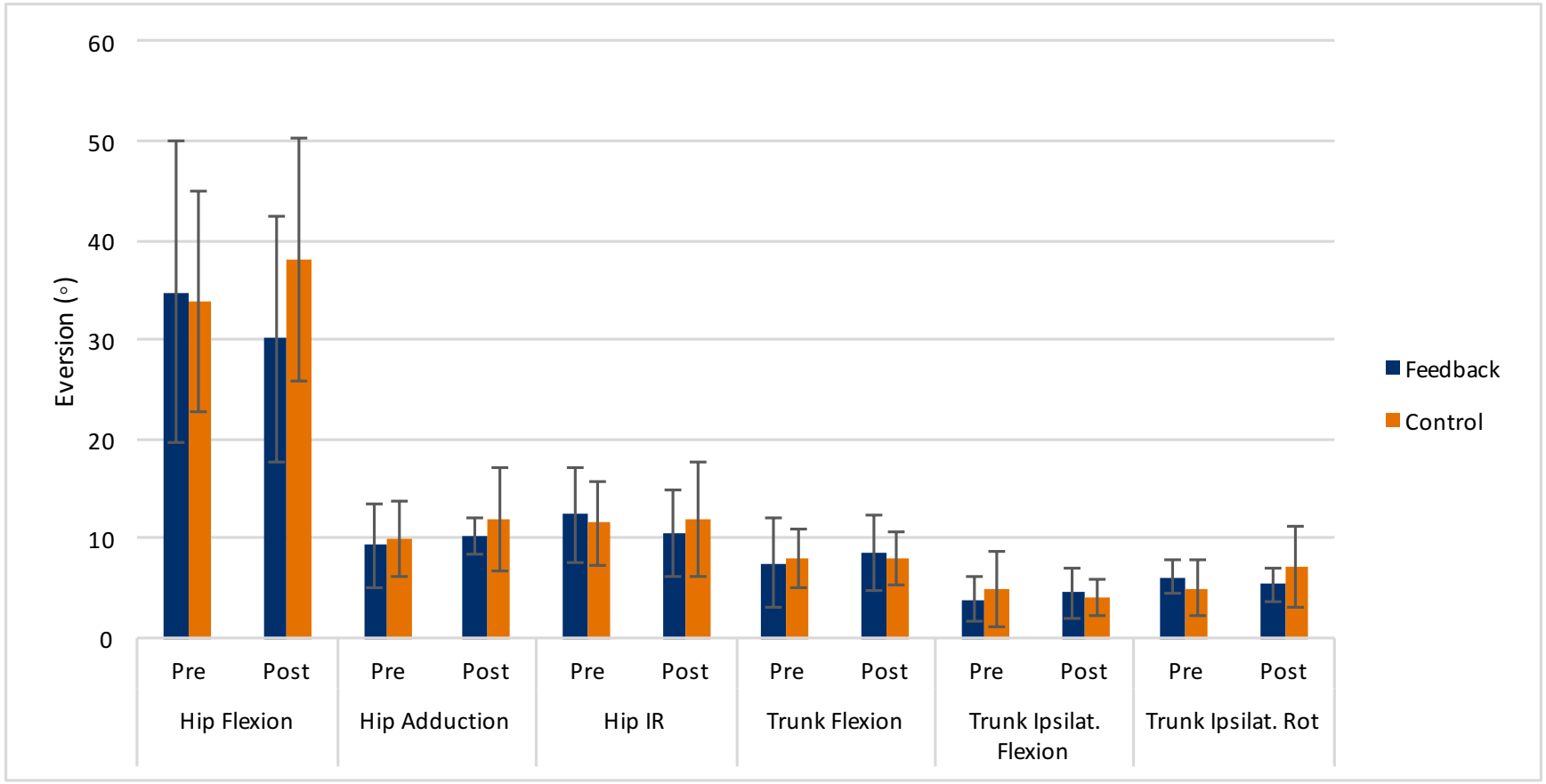


Figure D-7. Control Group Frontal and Transverse Plane Kinematic Variability Pre-Post Intervention

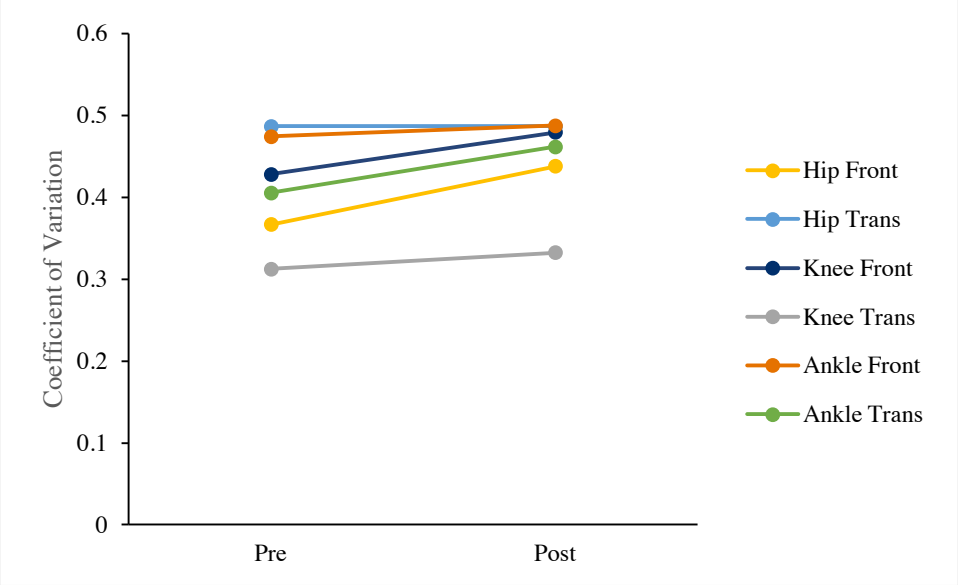
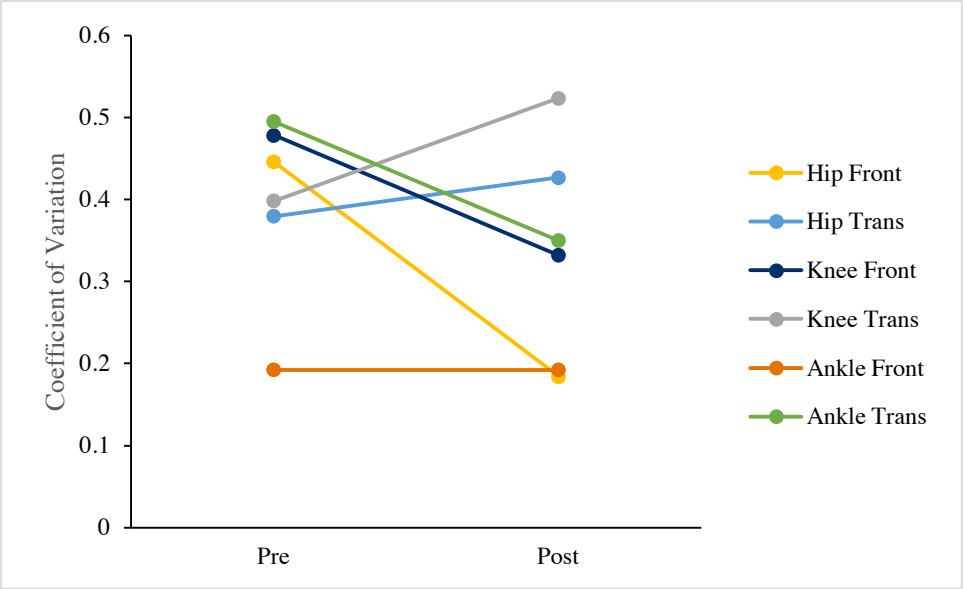


Figure D-8. Feedback Group Frontal and Transverse Plane Kinematic Variability Pre-Post Intervention



APPENDIX E
Recommendations for Future Research

- Can the Visual Single Leg Squat Test predict lower extremity injury?
- How do lower extremity kinetics differ between individuals with and without medial knee displacement during a single leg squat?
- Does the timing of lower extremity muscle activation differ between individuals with and without medial knee displacement during a single leg squat?
- In those with medial knee displacement, how do movement patterns during low intensity functional tasks compare with high intensity functional tasks?
- How does fatigue affect lower extremity movement patterns in those with medial knee displacement?
- Does visual feedback focused on correcting frontal plane knee kinematics in individuals with medial knee displacement have an effect on muscle activation or kinetics?
- What is the optimal number of visual feedback sessions to correct comprehensive lower extremity movement patterns in individuals with medial knee displacement?
- Can individuals with medial knee displacement, who are trained with visual feedback, retain biomechanical alterations?
- Does visual feedback focused on correcting frontal plane kinematics in individuals with medial knee displacement alter biomechanics during gait?

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