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Improving mechanical and neuromuscular deficits following anterior cruciate ligament reconstruction

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IMPROVING MECHANICAL AND NEUROMUSCULAR DEFICITS FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

By

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Improving rehabilitative practice following anterior cruciate ligament injury

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Despite consistent resolution of knee laxity and return to physical activity following ACL reconstruction, a growing body of evidence implicates impaired weight acceptance strategies as frequent primary drivers in a host of poor long-term outcomes. Most egregiously, the majority of the people with ACL reconstruction will show radiographic evidence of knee osteoarthritis within 15 years of surgery. Abnormal compression of the knee joint due to impaired knee flexion during weight acceptance is exacerbated by a tendency toward concomitant co-contraction of the knee musculature. Despite a plethora of proposed training paradigms, performance deficits after ACL reconstruction prove particularly resistant to enduring change. The studies included in this dissertation examine the mechanical and neuromuscular impairments in weight acceptance during landing from a jump that underlie the limitations to success following ACL reconstruction. A path toward improving functional recovery by treating impairments in landing is suggested and a novel training approach is tested. First, a cross-sectional study examines both the impaired patterns of neuromuscular recruitment in people who have returned to sporting activity following ACL reconstruction and their relationship to mechanics in landing. A pre-test/post-test laboratory study further examines the relationship between imposed changes in landing mechanics and co-contraction between the hamstrings and the quadriceps musculature. Clarification of neuromuscular activation and coordination impairments allows development of specific treatment techniques. To address limitations in current practice, a new device, the Bodyweight Reduction Instrument to Deliver Graded Exercise (BRIDGE), is validated in a third study, in which the effects of body weight support on the mechanics of repetitive single leg hopping are tested. The use of the BRIDGE is then described in a clinical case study. Finally, a randomized clinical trial determines whether high volume jump training with reduced loading intensity via body weight support will preferentially enhance motor learning for improved coordination of the neuromuscular system during high demand tasks such as single leg landing. This dissertation thereby advances the science of rehabilitation to more effectively target mechanical and neuromuscular impairments that devastatingly contribute to the risk of re-injury and early onset osteoarthritis following ACL reconstruction.

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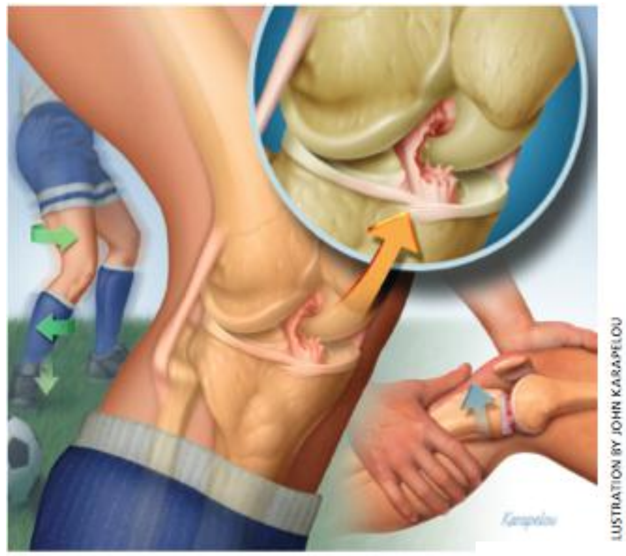
INTRODUCTION

The anterior cruciate ligament (ACL) is the most commonly injured ligament in the knee with hundreds of thousands of ACL tears each year;[1] indeed it is one of the most commonly injured ligaments in the human body.[2] The ACL is part of the ligamentous network maintaining weight-bearing stability between the femur and tibia (Figure 1). The ACL provides up to 80% of the resistance to anterior tibial shear on the femur during weight-bearing movement.[3] Its orientation dictates its function. From its proximal attachment along the posteromedial wall of the lateral femoral condyle, deep within the femoral notch, the ACL runs anteriorly and medially, attaching on the anterior aspect of the intercondyloid eminence of the tibial plateau, blending with the anterior horn of the medial meniscus.



Cimino, 2010

Approximately 70% of ACL injuries occur without contact with another person, while landing on a single leg.[4] Retrospective video analyses of injuries have shown that the position of highest risk occurs in the first moments of deceleration, when the foot is planted, the knee not yet fully flexed, and the tibia externally rotated in relation to the thigh. Due to the positioning during injury as well as the attachment points of the ACL, concomitant injuries to the medial meniscus, medial collateral ligament, and articular cartilage are common.[5,6] Athletes that participate in sports that involve cutting and pivoting, such as soccer, basketball, and lacrosse, are at higher risk.[4] The highest prevalence of ACL injury is in young athletes between 12 and 24 years of age.[6] The risk of ACL injury is also higher in young women, though the reasons behind the elevation in risk are contested.[7] Regardless, the incidence of ACL injury is higher in young men, because they are more likely to participate in cutting and pivoting sports, as well as contact sports such as football.[6]

While some people are able to return to activity and competitive sport without surgery, most require surgical reconstruction of the ligament in order to maintain stability of the knee during the physically demanding tasks associated with sport.[6,8] Most patients experience a relatively rapid return to physical activity after undergoing ACL reconstructive surgery.[9,10] For example, patients can walk without crutches within two weeks, and some patients return to running approximately three months following surgery.[11] However, many of the thousands of patients who have surgery each year are plagued by three key limitations to success: low rates of full return to pre-injury levels of participation, alarmingly high risk for another ACL tear, and an accelerated incidence of secondary knee osteoarthritis within 15 years following surgery. Given the disproportionately young and active population affected by ACL injury, the long-term consequences of ACL injury, even with surgical reconstruction, can be devastating.

The return to athletic activity at the pre-injury level is a primary motivation ACL reconstruction after injury. Within a year of surgery, it has been reported that 33% of patients achieve their goal to return to competitive sport.[12,13] However, by 2-7 years following surgery, less than 50% of patients have returned to their pre-injury level of competitive sport.[12] Interestingly, over 90% of patients have attempted return within 3 years following surgery or have participated in sport at a lower level than prior to their injury.[12] The reasons for the decrease in activity vary, and have only recently become a research priority. There is evidence that perceived function of the operated knee factors into the decision to alter or cease sports participated for at least half of those patients who do not return to competitive activity.[12]

The rate of initial ACL injury has been reported as 1 in 60 to 100 in female athletes participating in pivoting and cutting sports, and 1 in 500 in male athletes. Following ACL reconstruction, the risk for a second injury, whether the same or opposite side, increases to 1 in 4 female athletes who are participating in sports, and 1 in 7 male athletes.[14,15]

Knee osteoarthritis is one of the leading causes of disability worldwide, with a lifetime risk of 44.7%.[16] Risk factors for knee osteoarthritis include increased BMI, being female, aging to 50-75 years of age, and sustaining a previous knee injury,[17] the latter of which increases lifetime risk to 56.8%.[16] An estimated 5.1% of new knee osteoarthritis diagnoses are related to a previous injury.[17] The prevalence of symptomatic knee osteoarthritis in people who have had ACL reconstruction has been reported as between 42% and 90%.[18] Radiographic knee osteoarthritis has been found in 62% of patients with isolated ACL tears within 15 years of surgical reconstruction.[18] To be clear, a 15-year old athlete who sustains an ACL injury and has surgical reconstruction is more likely than not to present with radiographic osteoarthritis by the age of 30.

All three limitations in outcome have mechanical and neuromuscular components to their etiology. Athletes who undergo ACL reconstruction consistently show a pattern of mechanical and neuromuscular activation deficits in their operated limb in comparison to their healthy peers.[19-21] Acting as the fulcrum for the longest levers in the human body (the femur and tibia), the knee joint is the primary contributor to dissipation of load during landing tasks.[22,23] The quadriceps muscle, on the anterior thigh, shortens to straighten the knee, while the hamstring muscles, on the posterior thigh, flex the knee and extend the hip. Knee bending effectively creates a powerful torsion spring, storing mechanical energy within the quadriceps musculature.[24] Following ACL reconstruction, patients chronically avoid bending their operated knee when bearing weight, negating the ability of the knee to dissipate forces through the body.[25]

Patients' characteristic mechanical difficulties in accepting weight and attenuating load with the operated limb during movement patterns have clear negative functional consequences. Patients commonly exhibit a slow and incomplete restoration of normal knee motion utilized even in low demand tasks.[23,25] Restricted knee motion and small knee torques compared to the uninjured limb and healthy peers are hallmark findings in patients who exhibit activity limitations in walking speed and stair climbing ability in the first 8 weeks following surgery.[23] In physically demanding tasks, such as single leg landing from a hop, patients restrict knee flexion during deceleration, with reduced knee moments and increased rates of limb loading observed in comparison to the uninvolved limb.[26,27] Reduced knee flexion excursion and limited external knee flexion moments during landing are both correlated to reduced distance with a single leg hop.[28] Stiff landings with restricted knee motion also increase strain on the ACL as compared to soft landings with more knee flexion and larger moments, raising the risk of re-injury.[29]

The involved limb also responds to unanticipated movements or physically demanding tasks with an apparently protective co-activation of the knee flexors (hamstrings) and extensors (quadriceps) compared to the uninvolved side and healthy peers.[21,30] In vivo knee modeling suggests the movements and muscle recruitment patterns in the limb following ACL reconstruction are associated with increased knee compressive forces compared to healthy limbs.[21] Excessive compression is known to play a causative role in knee osteoarthritis.[31,32]

The relationship of co-contraction of the knee flexors and extensors to mechanics, function, and secondary risk factors is, however, debated in the literature, particularly in that pertaining to risk factors for initial injury. The hamstrings are described as one of the primary active restraints for anterior tibial translation during weightbearing activities. Renstrom et al.[33] published a seminal cadaveric study that demonstrated the line of pull of the hamstrings as being parallel to and protective of the passive restraint of the ACL at knee flexion angles greater than 30 degrees. A dominant theoretical construct is, therefore, that co-contraction of the hamstrings with the quadriceps during landing is a protective response to injury, and a normal and desirable outcome following ACL reconstruction.[34,35]

The studies included in this dissertation examine the mechanical and neuromuscular impairments underlying the limitations to success following ACL reconstruction, and suggest a path toward improving functional recovery by treating said impairments. First, a cross-sectional study examines both the impaired patterns of neuromuscular recruitment in people who have returned to sporting activity following ACL reconstruction and their relationship to mechanics in landing. A pre-test/post-test laboratory study further examines the relationship between imposed changes in landing mechanics and co-contraction between the hamstrings and the quadriceps musculature. Clarification of neuromuscular activation and coordination impairments allows development of specific treatment techniques. To address limitations in current practice, a new device is developed and validated in a third study, in which the effects of body weight support on the mechanics of repetitive single leg hopping are tested. The use of this particular device, dubbed the Bodyweight Reduction Instrument to Deliver Graded Exercise (BRIDGE), is then described in a clinical case study. Finally, a randomized clinical trial determines whether high volume jump training with reduced loading intensity via body weight support will preferentially enhance motor learning for improved coordination of the neuromuscular system during high demand tasks such as single leg landing. In so doing, this dissertation advances the science of rehabilitation to more effectively target mechanical and neuromuscular impairments that so devastatingly contribute to the risk of re-injury and early onset osteoarthritis following ACL reconstruction. The following sections provide additional introduction for each study, organized by chapter and question.

Chapter 2

How does muscle recruitment patterning differ between athletes with a contact vs. a non-contact mechanism of injury?

Nearly 70% of all ACL injuries occur without contact with another player.[4] Underlying neuromuscular deficits in coordination of the thigh musculature are thought to increase the risk of these "non-contact" injuries.[29,36] The extent to which the mechanism of injury of a patient with ACL reconstruction affects the muscle activation patterns during sport-specific tasks after surgery is unknown. Certainly, co-contraction has also been associated with elevated compression within the knee joint,[21] elevating the risk of osteoarthritis.[31] The pattern of co-contraction between the quadriceps and hamstrings has also been associated with athletes who lack the ability to dynamically stabilize their knee, elevating the risk of re-injury.[30] People with ACL-deficient knees (following injury, but prior to surgery) who are able to return to all pre-injury activity, including sports, for at least one year are defined as "copers."[37] People with a non-contact mechanism of injury are less likely to be classified as copers,[38] and those classified as non-copers tend to have higher levels of co-contraction between the hamstrings and quadriceps than copers during hop landing and walking.[39] The potential pre-surgical relationship between mechanism of injury and co-contraction has not been explored further, but suggests that differences in coordination of the thigh musculature between people with a contact vs. a non-contact injury may play into expected outcomes following ACL reconstruction.

Purpose: To determine whether mechanism of ACL injury affects co-contraction of the hamstrings with the quadriceps following ACL reconstruction.

Hypothesis 1: Individuals with a non-contact mechanism of injury will exhibit more co-contraction than individuals with a contact mechanism of injury.

Hypothesis 2: There will be coordination differences between limbs, with the operated limb exhibiting higher co-contraction.

Chapter 3

What is the neuromuscular response to improved mechanics in landing?

Pre-surgically, potential copers who are trained to more effectively stabilize their knee during movement demonstrate decreased co-contraction.[40] Co-contraction is therefore a potentially modifiable risk factor for post-surgical osteoarthritis. Further, the mechanical deficits observed after ACL reconstruction appear amenable to training.[41,42] Landing instruction can promote softer landings with greater knee flexion and external knee moments, decreasing the risk of re-injury.[42] Training of landing mechanics is recommended as a final step in return-to-sport rehabilitation in recently published practice guidelines for ACL reconstruction rehabilitation.[9,10] The effect of landing instruction on hamstrings and quadriceps co-contraction after surgery is, however, unknown. If co-contraction is a modifiable risk factor for osteoarthritis, it is imperative to understand the effects of landing instruction on the coordination of the thigh musculature.

Purpose: To determine changes in the neuromuscular control of the quadriceps and hamstrings following instructions aimed at improving knee flexion during a single limb landing task in persons who have undergone ACL reconstruction.

Hypothesis 1: Landing performance of the operated limb will improve following instruction in landing technique, as measured by increased knee flexion angle and increased external knee flexion moments, and decreased peak vertical ground reaction forces compared to pre-instruction values.

Hypothesis 2: Co-contraction of the hamstrings and quadriceps will decrease following instruction in landing technique.

Chapter 4

Can intensity of landing be modified while maintaining task-specificity?

Although landing instruction results in a transient effect on mechanics, and training of landing mechanics is recommended as a final step in return-to-sport rehabilitation following ACL reconstruction, the retention of the positive effects of training is unknown. Plyometric, or jump, training seems to be the one commonality in successful ACL injury risk reduction programs and is included in all current ACL reconstruction rehabilitation recommendations.[9,10,43] It is unknown, however, how much training is necessary following injury. Further, given that "training" encompasses parameters such as intensity, repetition, and duration, the relationship between these parameters as they influence motor learning, and thereby retention of the positive effects of training, is unclear.

Plyometric training involves higher joint loads than most other activities, and so is generally performed with low repetition.[44] For example, the body generally absorbs approximately 1.2 body weights of vertical ground reaction force while walking.[24] In contrast, the body regularly absorbs over 3 body weights of vertical force during a jump landing.[41] Elite uninjured athletes normally perform fewer than 100 repetitions per training session, with only 1-2 training sessions per week.[45-47] Injury and surgical status provide further limitations. Financial and motivational issues at the end of a long rehabilitation process may limit the time available for plyometric training, but intrinsic issues with the training paradigm itself may be the primary limiting factors to repetition of the landing task. Clinicians will commonly limit practice of jumping tasks to avoid potential harm to the joint surfaces and exacerbation of osteoarthritic effects.[44,48] Retraining efforts may also be self-limited by athletes who restrict their knee loading during jump landing due to fear of injury or lack of confidence in the operated limb.[49]

Limiting practice is understandable when patients are fearful and is prudent for safety reasons. However, restricting retraining starkly contrasts with the current literature on motor learning after injury, which emphasizes high repetition to reestablish normal movement patterns.[50] In studies of interventions aimed at creating habitual movement patterns in the arm and hand, as well as in studies examining programs to restore gait following neurological injury, extensive training has been needed to solidify changes.[51,52] In one study examining the effects of jump training on healthy athletes, dosages as high as 270-690 repetitions per session were needed to see changes in motor recruitment patterning.[45]

Increased repetition is generally accompanied by decreased intensity during training. However, attempting to reduce intensity during jump landing is challenging. Current recommendations are to lower the height of the jump,[44] but large and rapid limb loading occurs even when landing from a single leg hop or even when jumping up to a surface. The primary problem in returning injured athletes to optimal performance and decreasing the risk of re-injury and the long-term risk of osteoarthritis potentially lies within the relationship between intensity and repetition during plyometric training.

Body weight support has been used in gait retraining as a remedy to the problem of limited repetition due to fear and high relative intensity, particularly following neurological insult.[52] A recent systematic review found that body-weight supported treadmill walking improved walking speed and endurance in patients with stroke more than training without support. Compared with people who trained without support, patients improved their walking speed by 0.07 m/s and were able to walk approximately 60 meters further.[53] Prior efforts to mitigate excessive loading with sporting tasks have used three methods: aquatic therapy, plyometric leg press, or commercial body weight support systems such as the AlterG or ZeroG.

The aquatic environment does support the center of mass and provide effective mitigation of load. However, the level of body submersion defines the level of body weight support. When the level of body submersion changes drastically, as when performing a jump from a full squat, the level of body weight support changes as well.[54] Further, speeds of movement differ dramatically from land-based exercise due to hydraulic forces, which can also create abnormal shear torques through joints due to turbulence and pressure gradients.[54] Alternatively, a plyometric leg press can allow patients to practice jumping or hopping in place with reduced load. However, gravitational forces continue to be felt by the body, and the athlete must utilize additional muscles to maintain the leg in a position for landing. A plyometric leg press is also confined to a small landing platform, disallowing sport specific training. Body weight support systems such as the AlterG are bound over a treadmill. More importantly, the unweighting force is provided by lifting the center of mass to a specified height, which does not allow for more than 2-5 cm of horizontal or vertical translation of the center of mass. As such, jump training is not an option with these systems.

The BRIDGE unweighting system, in contrast, allows athletes to complete sporting tasks such as jumping and hopping with unrestricted joint motion while receiving a consistent unweighting force. There is significant evidence, though, that body weight support can substantially modify the intrinsic mechanics of weight-bearing tasks, particularly walking and running.[55,56] As plyometric tasks conform to a bouncing, or elastic, gait pattern, such as running, the effects of body weight support on repetitive hopping are important to elucidate when considering body weight support as a treatment option.

Purpose: To examine the effects of progressive body weight support on the mechanical characteristics of a repetitive single leg plyometric task within a rehabilitative context.

Hypothesis 1: The body weight support system will provide consistent support throughout the hopping task.

Hypothesis 2: As body weight support increases, overall ground reaction forces and joint moments will progressively decrease, while kinematics will remain unchanged, thereby preserving the task specificity of training.

Chapter 5

Can the modifications to training dosage made possible by body weight support result in effective treatment?

The BRIDGE body weight support system may allow the freedom to prescribe the high repetition practice hypothesized to be necessary to the development of more responsive biomechanical and neuromuscular patterns in landing. Theoretically, as desired patterns become habitual, the unweighting force can be weaned away to encourage use of the new patterns under normal loading requirements. In this way, higher repetition with lower intensity can overcome the major limitation to plyometric training—excessive intensity that limits task practice.

A potential problem with the use of body weight support when training an intrinsically high intensity task, however, may be that lowering the intensity of the task may not provide a high enough stimulus for motor adaptation and learning to affect performance in sports-related tasks. A description of possible adaptation of a plyometric training program adapted to the body weight support environment is necessary for further study. Further, an initial description of the clinical experience of training with body weight support is necessary to develop further examination of the effectiveness of body weight support as an intervention strategy.

Purpose: To report the outcomes of a patient with a previous history of ACL reconstruction treated with high repetition jump training coupled with body weight support as a primary intervention strategy. Changes in landing mechanics, psychological readiness for activity, and functional outcomes are detailed.

Chapter 6

Are the mechanical and neuromuscular coordination effects of a high-repetition training intervention superior to those of a best-practice training intervention with relatively lower repetitions of practice?

Whether the changes in mechanics and function made within the confines of the described case report are similar to or better than what would have been possible with standard plyometric training is, by the nature of the case study design, unknown. Indeed, outcomes to standard plyometric training programs in a population with ACL reconstruction are themselves unknown, providing a poor comparison. Elucidating the overall beneficial effects of a best-practice plyometric training program on the neuromuscular, mechanical, and functional qualities of an injured population is therefore important and, in and of itself, advances the treatment of athletes with ACL reconstruction. Relatively few studies have examined the effects of jump training following ACL reconstruction, only one study has examined mechanical effects, and there are no studies to date that have examined the neuromuscular effects of jump training.

Neuromuscular behaviors, in particular, are difficult to detect in a clinical setting. The relatively easily seen mechanical behaviors must serve as informational proxies, and potentially allow inference of the level of co-contraction within the operated limb during landing. The retention of neuromuscular coordination following landing training is therefore of particular interest, and may be the outcome most affected by the relationship between intensity and repetition that is modulated with body weight supported jump training. Only one study to date has compared the effects of high and low volume plyometric training following ACL reconstruction.[57] Participants in the higher volume training group demonstrated greater improvements in functional performance measures such as single leg hop for distance.[57] Biomechanical and neuromuscular performance measures such as knee flexion, VGRF, and co-contraction were not measured, however. Additionally, the volumes in the high volume training group were much lower than what is theorized to generate lasting change, and retention of improvements was not measured.

Purpose 1: To examine the impact of an extended plyometric training program on patient-reported function and biomechanical measures

Purpose 2: To determine whether a high repetition program with decreased intensity via BWS will improve functional, mechanical, and neuromuscular outcomes

Hypothesis 1: Plyometric training, whether low or high repetition, will improve functional, mechanical, and neuromuscular outcomes.

Hypothesis 2: High repetition training will result in improved retention of functional, mechanical, and neuromuscular gains.

In sum, the series of studies included in this dissertation advance the understanding of the neuromuscular and mechanical deficits and coalesce to increase the risk of secondary

problems following ACL reconstruction. Despite consistent resolution of knee laxity and return to physical activity following ACL reconstruction, a growing body of evidence implicates commonly impaired weight acceptance strategies as primary drivers in a host of poor long-term outcomes. Most egregiously, the majority of the people with ACL reconstruction will show radiographic evidence of knee osteoarthritis within 15 years of surgery. Abnormal loading is exacerbated by a tendency toward protective co-contraction of the knee musculature, leading to even greater joint compression. Despite a plethora of proposed training paradigms, performance deficits after ACL reconstruction prove particularly resistant to enduring change. After exploring mechanical and neuromuscular performance factors, their relationship to each other, and the effects of conscious changes in landing technique, a novel treatment approach adhering to sound motor learning principles is proposed. The treatment approach is developed through a case study description, and, finally, pilot testing of the intervention compares outcomes to a best practice model. By effectively targeting neuromuscular impairments, the goal of this dissertation is to develop a treatment paradigm to induce substantial and persistent changes in muscle recruitment patterns while safely restoring normal force absorption performance of the knee.

References

1. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med.* 2014;42(10):2363-2370.
2. Clayton RA, Court-Brown CM. The epidemiology of musculoskeletal tendinous and ligamentous injuries. *Injury.* 2008;39(12):1338-1344.
3. Butler DL, Noyes FR, Grood ES. Ligamentous restraints to anterior-posterior drawer in the human knee. A biomechanical study. *J Bone Joint Surg Am.* 1980;62(2):259-270.
4. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.
5. Hurd WJ, Axe MJ, Snyder-Mackler L. A 10-year prospective trial of a patient management algorithm and screening examination for highly active individuals with anterior cruciate ligament injury: Part 1, outcomes. *Am J Sports Med.* 2008;36(1):40-47.
6. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *Am J Sports Med.* 2005;33(10):1579-1602.
7. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(8):859-879.
8. Rudolph KS, Axe MJ, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? *Knee Surg Sports Traumatol Arthrosc.* 2000;8(5):262-269.
9. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.
10. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
11. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. *J Orthop Sports Phys Ther.* 2012;42(3):153-171.
12. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2012;40(1):41-48.
13. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538-543.
14. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.

15. Shelbourne KD, Gray T. Minimum 10-year results after anterior cruciate ligament reconstruction: how the loss of normal knee motion compounds other factors related to the development of osteoarthritis after surgery. *Am J Sports Med.* 2009;37(3):471-480.
16. Murphy L, Schwartz TA, Helmick CG, et al. Lifetime risk of symptomatic knee osteoarthritis. *Arthritis Rheum.* 2008;59(9):1207-1213.
17. Silverwood V, Blagojevic-Bucknall M, Jinks C, Jordan JL, Protheroe J, Jordan KP. Current evidence on risk factors for knee osteoarthritis in older adults: a systematic review and meta-analysis. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society.* 2015;23(4):507-515.
18. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *Am J Sports Med.* 2010;38(11):2201-2210.
19. Gauffin H, Tropp H. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med.* 1992;20(2):182-192.
20. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998;8(6):349-362.
21. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
22. Nyland J, Wera J, Klein S, Caborn DN. Lower extremity neuromuscular compensations during instrumented single leg hop testing 2-10 years following ACL reconstruction. *Knee.* 2014;21(6):1191-1197.
23. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther.* 2000;80(3):251-260.
24. Cavagna GA, Saibene FP, Santi GF, Margaria R. Analysis of the Mechanics of Locomotion. *Experimental medicine and surgery.* 1963;21:117-126.
25. Chmielewski TL. Asymmetrical lower extremity loading after ACL reconstruction: more than meets the eye. *J Orthop Sports Phys Ther.* 2011;41(6):374-376.
26. Deneweth JM, Bey MJ, McLean SG, Lock TR, Kolowich PA, Tashman S. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee during a single-legged hop landing. *Am J Sports Med.* 2010;38(9):1820-1828.
27. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports.* 2010;20(1):e12-19.
28. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(11):1587-1593.

29. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *J Biomech.* 2011;44(10):1845-1851.
30. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9(2):62-71.
31. Block JA, Shakoor N. Lower limb osteoarthritis: biomechanical alterations and implications for therapy. *Curr Opin Rheumatol.* 2010;22(5):544-550.
32. Vincent KR, Conrad BP, Fregly BJ, Vincent HK. The pathophysiology of osteoarthritis: a mechanical perspective on the knee joint. *PM R.* 2012;4(5 Suppl):S3-9.
33. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14(1):83-87.
34. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am J Sports Med.* 1988;16(2):113-122.
35. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* 1987;15(3):207-213.
36. Dai B, Herman D, Liu H, Garrett WE, Yu B. Prevention of ACL injury, part II: effects of ACL injury prevention programs on neuromuscular risk factors and injury rate. *Res Sports Med.* 2012;20(3-4):198-222.
37. Chmielewski TL, Rudolph KS, Snyder-Mackler L. Development of dynamic knee stability after acute ACL injury. *J Electromyogr Kinesiol.* 2002;12(4):267-274.
38. Hurd WJ, Axe MJ, Snyder-Mackler L. Influence of age, gender, and injury mechanism on the development of dynamic knee stability after acute ACL rupture. *J Orthop Sports Phys Ther.* 2008;38(2):36-41.
39. Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. *J Electromyogr Kinesiol.* 2005;15(1):83-92.
40. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* 2005;85(8):740-749; discussion 750-744.
41. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
42. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
43. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *J Strength Cond Res.* 2012;26(8):2272-2292.

44. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *J Orthop Sports Phys Ther.* 2006;36(5):308-319.
45. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. *J Athl Train.* 2004;39(1):24-31.
46. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* 2005;39(12):932-938.
47. Vaczi M, Tollar J, Meszler B, Juhasz I, Karsai I. Short-term high intensity plyometric training program improves strength, power and agility in male soccer players. *J Hum Kinet.* 2013;36:17-26.
48. Chmielewski TL, Trumble TN, Joseph AM, et al. Urinary CTX-II concentrations are elevated and associated with knee pain and function in subjects with ACL reconstruction. *Osteoarthr Cart.* 2012;20(11):1294-1301.
49. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2013;41(7):1549-1558.
50. Kerr AL, Cheng SY, Jones TA. Experience-dependent neural plasticity in the adult damaged brain. *J Comm Disord.* 2011;44(5):538-548.
51. Fine MS, Thoroughman KA. Motor adaptation to single force pulses: sensitive to direction but insensitive to within-movement pulse placement and magnitude. *J Neurophysiol.* 2006;96(2):710-720.
52. Combs SA, Dugan EL, Ozimek EN, Curtis AB. Bilateral coordination and gait symmetry after body-weight supported treadmill training for persons with chronic stroke. *Clin Biomech (Bristol, Avon).* 2013;28(4):448-453.
53. Mehrholz J, Pohl M, Elsner B. Treadmill training and body weight support for walking after stroke. *Cochrane Syst Rev.* 2014;1:CD002840.
54. Haupenthal A, Ruschel C, Hubert M, de Brito Fontana H, Roesler H. Loading forces in shallow water running in two levels of immersion. *J Rehabil Med.* 2010;42(7):664-669.
55. Threlkeld AJ, Cooper LD, Monger BP, Craven AN, Haupt HG. Temporospatial and kinematic gait alterations during treadmill walking with body weight suspension. *Gait & posture.* 2003;17(3):235-245.
56. Donelan JM, Kram R. Exploring dynamic similarity in human running using simulated reduced gravity. *J Exper Biol.* 2000;203(Pt 16):2405-2415.
57. Souissi S, Wong del P, Dellal A, Croisier JL, Ellouze Z, Chamari K. Improving Functional Performance and Muscle Power 4-to-6 Months After Anterior Cruciate Ligament Reconstruction. *J Sports Sci Med.* 2011;10(4):655-664.

ACTIVATION PATTERNING OF THE THIGH MUSCULATURE DURING LANDING VARIES WITH MECHANISM OF INJURY FOLLOWING ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION

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The project was reviewed and approved by the
Institutional Review Board of the University of Montana.

Purpose: To determine whether mechanism of anterior cruciate ligament (ACL) injury affects co-contraction of the hamstrings with the quadriceps during jump landing following ACL reconstruction. Increased co-contraction has been implicated in an increased risk for knee osteoarthritis following ACL reconstruction. Also, those athletes with poor potential for success with non-operative treatment after ACL injury exhibit marked co-contraction during hop landing. We hypothesized that co-contraction during hop landing would be increased in those athletes with a non-contact mechanism of injury.
Methods: Nineteen athletes with contact and 36 with non-contact injuries underwent biomechanical and electromyographic analysis of a single-leg landing task nearly two years after surgery. Differences between groups and between limbs in lower extremity sagittal joint angles, moments, and co-contraction were compared.
Results: The non-contact group had significantly higher co-contraction than the contact group in the uninvolved limb ($p=0.04$). The contact group had significantly higher co-contraction in the involved limb ($p=0.004$). The co-contraction of the involved limb of the contact group was not significantly different from that of either limb of the non-contact group ($p>0.08$). There were no significant differences in kinematic or kinetic variables between the contact and non-contact groups ($p>0.1$). There was a significant difference in peak knee moment between the involved and non-involved limbs in both groups ($p<0.001$).
Conclusions: Athletes with a non-contact mechanism of ACL injury demonstrate higher co-contraction in both limbs during hop landings long after surgery. Excessive co-contraction could have important negative implications for osteoarthritis development and future second ACL injury risk.
Key Words: co-contraction, osteoarthritis risk, ACL outcomes, EMG
Level of Evidence: Level II Prognostic Study

The anterior cruciate ligament (ACL) is the most frequently injured ligament of the knee [1], with the highest prevalence in young athletes.[2] The majority of people who injure their ACL intend to return to their previous level of activity.[3] Those people that choose to return to sports that include tasks such as jumping, hopping, cutting, and pivoting frequently choose to surgically restore ligamentous stability of the knee joint. Of the hundreds of thousands of injured athletes each year, more than 60% undergo surgical ACL reconstruction.[4]

While a variety of mechanisms of injury (MoI) have been identified, an estimated 70% of ACL injuries are non-contact in nature,[5] defined as injury in the absence of player-to-player contact.[6] In contrast, a contact ACL injury occurs as a result of either a direct blow to the knee (direct) or during player-to-player contact such as during a tackle (indirect).[5] Intrinsic faults in the coordination of the thigh musculature are thought to contribute to the risk of a non-contact ACL injury.[5,7,8] Kinematic faults in jump landing, such as decreased knee flexion angle and external flexion moments, are also considered risk factors for non-contact ACL injury, and may be related to muscle coordination deficits.[5] It is unknown whether pre-injury neuromuscular faults in muscle activation patterning present prior to injury persist following surgery. It is reasonable to postulate that the neurological control of the thigh musculature in those athletes with a non-contact MoI may influence their postoperative outcomes.

In particular, muscle activation patterns of the thigh muscles during sports tasks may play a role in important shortcomings in long-term surgical outcomes. An estimated 50% of people with ACL reconstruction will present with radiographic evidence of early-onset osteoarthritis of the knee within 10-15 years following surgery.[9,10] Many factors contribute to the risk of knee osteoarthritis following ACL reconstruction, but excessive mechanical compression through the knee joint during movement may increase the risk of joint breakdown.[11] In vivo modeling has demonstrated increased joint compression directly related to the amount of co-contraction of the hamstring musculature with the quadriceps in the surgical knee during a single leg countermovement activity.[12] The compressive effects of co-contraction of the quadriceps and hamstring muscle groups have important implications to the development and progression of knee osteoarthritis following ACL injury.

Another important shortcoming after ACL reconstruction is that the risk of second ACL injury in athletes who return to sport increases more than 5-fold over that of their uninjured peers.[13-15] The same risk factors that contributed to the original ACL injury may continue to increase the risk for a second ACL injury following surgery.[16-18] Impairments in muscle activation patterning that contributing to the initial non-contact ACL injury may persist after surgery and contribute to increasing risk for a second ACL injury.

Potential differences in co-contraction between people with contact and non-contact MoI may play into the design of post-operative rehabilitative plans of care or perhaps the decision making scheme for return to sport. The relative contribution of co-contraction between the hamstring and quadriceps muscle groups to ACL injury risk is a matter of debate in the current literature. Co-contraction of the thigh musculature has been postulated to decrease risk of ACL injury by allowing the hamstrings to generate a posterior tibial force, controlling the forces from the quadriceps.[19] In contrasting findings, co-contraction of the quadriceps and hamstrings during functional tasks has been associated with athletes who lack the ability to dynamically stabilize their knee following ACL injury.[20] People with ACL- deficient knees who are able to return to all pre-injury activity, including sports, without symptoms of knee instability for at least 1 year have been called “copers”.[21] Extended work with copers and non-copers has demonstrated that people with a non-contact MoI are less likely to be classified as copers.[22] Copers also tend to have lower levels of co-contraction than non-copers.[23] Further, training potential copers to dynamically stabilize their knee on unstable support surfaces (perturbation training) induces a reduction in co-contraction.[24] Post-surgically, decreased co-contraction has been demonstrated following instruction for optimal kinematics during both countermovement jumps and absorptive jump landings.[25,26] Lower levels of co-contraction have thus been associated with enhanced neuromuscular control and improved dynamic stability, all of which could decrease risk of ACL re-injury.

Co-contraction is therefore a potentially modifiable risk factor for post-surgical osteoarthritis. Improved understanding of the nature of the relationship between MoI and co-contraction of the thigh muscles will lead to a more effective estimation of injury risk and appropriate prioritization of neuromuscular retraining following surgery. The purpose of this study is to examine the activation patterning of the quadriceps and hamstrings muscles during hop landing for both the involved and uninvolved limbs of those people with non-contact and contact injuries. Our primary hypothesis is that those individuals with non-contact MoI will exhibit more co-contraction than those individuals with a contact MoI. Secondarily, we hypothesize that there will be differences between limbs with the involved limb exhibiting higher co-contraction.

METHODS

Subjects

Fifty-five athletes were sampled by convenience from a population of 12-35 year old recreational or competitive athletes (Tegner Activity Scale ≥4)[27] who had undergone ACL reconstruction between 6 and 48 months previously and had been cleared for and returned to their normal activities (**TABLE 1**). The dataset is in continuous development; as a result, data from 28 of these athletes has been included in previous work.[25] Their injuries were classified as contact or non-contact according to their description of the incident. Subjects were excluded if they had 1) more than two ACL surgeries on the same leg, or bilateral ACL injuries, 2) history of a posterior cruciate ligament injury, 3) a lower extremity of trunk injury that prevented normal activities of daily living within the 6 months prior to testing. Subjects were also excluded if their injury was not classifiable as contact or non-contact. This criterion predominantly excluded those potential subjects injured through skiing or snowboarding accidents. All subjects provided signed informed consent as approved by the University of Montana Institutional Review Board.

Table 1. descriptive characteristics of subjects (Mean ± SD)

Group	Contact	Non-contact
Gender	7 male; 13 female	16 male; 20 female
Age	21.0±4.6	21.9±4.5
Body Mass Index	24.8±2.3	24.2±2.8
IKDC[a] Score	84.3±10.2	84.2±9.9
Preferred Sports		
Basketball	5	12
Soccer	4	9
Volleyball	2	1
Football	4	4
Other	5	10
Time since surgery	18.4±14.2	25.6±14.9
Graft Type		
BPTB[b]	9	10 + 2 revisions
Hamstring	9	22 + 2 revisions
Allograft	2 + 2 revisions	4

[a] IKDC, International Knee Documentation Committee Subjective Knee Form
[b] BPTB, bone-patellar tendon-bone

Testing Procedures

Subjects initially completed the International Knee Documentation Committee Subjective Knee Form (IKDC)[28,29] as a measure of subjective function before undergoing a one-time testing session using protocols previously described.[25] Testing consisted of, in order, a five-minute treadmill walking warm-up, surface electromyography (sEMG) electrode placement, maximal voluntary isometric contraction (MVIC) testing, placement of reflective markers, standing kinematic data calibration, and motion analysis assessment of a single leg landing task.

Single-Leg Landing Task

We chose to investigate a single-leg landing task as previously described.[25,30] The mechanism of a non-contact ACL injury typically involves a single leg landing from a hop,[5] and we hoped to use this task to highlight compensatory patterning that might otherwise be missed in a double-leg task. Subjects stood approximately 10 cm from the edge of a 20 cm box with their hands on their hips, and were instructed to gain their balance on a single leg before hopping forward off the box with their eyes looking forward (**FIGURE 1**). A successful trial required maintaining single leg stance for at least two seconds upon landing, and regaining dual stance in a controlled manner. Subjects performed five successful recorded trials of the task following at least 4 practice repetitions for task familiarization.

Figure 1. Subject with full retroreflective marker set, during single leg landing task from 20 cm box.

Biomechanical Analysis

Kinematic and kinetic analysis was performed using an 8-camera VICON system (F40 cameras, Oxford Metrics, Ltd., London, UK) using their Nexus software with video data sampled at 200 Hz. A 400 x 600 mm force plate (AMTI, Watertown, MA) captured tri-planar ground reaction forces during landing with data sampled at 1200 Hz. Retro-reflective markers (14 mm diameter) were attached to bilateral bony landmarks to identify the joint centers of the ankle, knee, and hip. Markers were placed at the top of the iliac crest to define the height of the pelvis. Additional noncollinear tracking cluster markers were placed on the lateral shanks, lateral thighs, and sacrum. Markers on the 1st and 5th metatarsal heads and the superior and inferior heel counter of the shoe tracked foot movement. A standing calibration was performed prior to testing to identify joint centers with respect to each segment's coordinate system. Joint center anatomical markers were then removed. Marker trajectories and force plate data were respectively low pass filtered at 12 and 50 Hz with 4th order phase-corrected Butterworth filters. The peak vertical ground reaction forces (VGRF) and joint moments were normalized to each individual's body mass. Joint kinematics were calculated using Euler angles, and joint kinetics were calculated with inverse dynamics using rigid body analysis through custom applications with Visual3D software (Visual3D, Version 4.75.29, C-Motion Inc., Rockville, MD). Joint angles and moments were time normalized to 100 increments from 100 milliseconds prior to initial contact on the force plate to peak knee flexion during landing (ie, the weight acceptance phase).[18,31,32] The normalization enables the calculation of an ensemble average across trials for each subject, as the time taken to complete weight acceptance varies slightly within and between subject trials.

Muscle activation levels were recorded from the vastus lateralis (VL) and biceps femoris (BF) via a Bagnoli sEMG system (Delsys Inc., Boston, MA) interfaced with the VICON system with a 16-bit analog-digital converter. Differential surface electrodes with a 10 mm long x 1mm diameter silver bar contacts with a 10 mm spacing distance were placed mid-muscle belly and oriented along the muscle fibers, taped in place, and wrapped with elastic wraps to ensure minimal movement artifact. Signals were preamplified at the interface, amplified at the system level with a gain of 1000, and sampled at 1200 Hz. Using Visual3D software as above, signals were bandpass filtered at 20-350 Hz and full-wave rectified before a linear envelop was created with a 10 Hz low-pass phase corrected Butterworth filter. Prior to testing, sEMG signals from each muscle were obtained from maximum voluntary isometric contraction (MVIC) testing as described below for normalization purposes, and signal normalized to peak signal during MVIC was used during all subsequent analyses.

Muscle activation levels of the knee flexor and extensor muscles during MVIC were determined with a Kin-Com 125AP dynamometer (Chattanooga Group, Inc., Chattanooga, TN) utilizing previously published methods.[25,33] The uninvolved limb was tested first. Patients were seated and secured in place with the knee placed at 90° (vastus lateralis) and 60° (biceps femoris) of flexion for testing. Visual force trace data and vigorous verbal encouragement were used during testing to elicit a three second maximal contraction. After progressive warm-up contractions, testing was repeated with 60-90 seconds rest between trials until maximum force increased by less than 5% or decreased between trials. The forces generated were sampled at 200 Hz utilizing a BIOPAC MP 150 (BIOPAC Systems Inc., Santa Barbara, CA) data acquisition workstation with Acqknowledge v.3.7 software and processed with a 6 Hz low pass filter prior to determining MVIC. The trial with the greatest torque produced was used to obtain the maximal signal intensity for normalization of the sEMG during dynamic hop trial. The highest muscle activation levels recorded during the selected MVIC trial were utilized for normalization for each respective muscle as detailed above.

Data Processing and Analysis

Instantaneous co-contraction was defined as the weighted ratio between hamstring and quadriceps activation, and the co-contraction index (CoI) as the integral of that function across the weight acceptance phase of landing:

$$\int_{100\ ms\ before\ land}^{Peak\ knee\ flex} \frac{EMG_L}{EMG_H} * (EMG_L + EMG_H)$$

where EMG_L is the normalized activation of the less active muscle and EMG_H is the normalized activation of the more active muscle. This method combines estimations of the magnitude of co-contraction as well as relative muscle recruitment.[20]

Descriptive statistics were prepared for all variables of interest and clinical measures of outcomes. No significant outliers were found. Kinematic and kinetic variables were compared by two-way ANOVA with main effects of limb and group for VGRF, peak joint angles, and peak joint moments. Post-hoc independent t-tests compared means between groups, while paired t-tests compared between limbs. However, equal variance and sample size assumptions between groups were not met with the EMG data (Bartlett's K-squared = 8.66, p = 0.003). While balanced sampling can mitigate unequal variance, with unbalanced sampling the results of ANOVA testing can confound statistical interpretation due to the sensitivity of the F-statistic to the variance of the larger sample.[34] One-sided independent t-tests with a Welch approximation of the degrees of freedom were therefore utilized to compare muscle activation patterns via mean CoI between groups (contact v. non-contact MoI). Effect sizes by group and limb involvement were determined by Cohen's *d.* Statistical tests were performed in R (version 3.1.3) with an alpha level of $P \leq 0.05$.

Table 2. Neuromuscular activation through the weight acceptance phase of a single leg landing. Descriptive statistics are reported as Mean(SD).

	Involved Limb			Uninvolved Limb		
Measure	Contact	Non-contact	P	Contact	Non-contact	P
Co-contraction Index	25.1 (9.3)	30.3 (18.2)	0.08	19.81 (8.0)	24.42 (10.6)	0.04*
Quadriceps	42.8 (16.0)	43.2 (13.5)	0.46	43.5 (15.7)	45.5 (15.6)	0.33
Hamstrings	24.3 (20.4)	23.5 (13.3)	0.56	16.7 (6.0)	20.9 (8.4)	0.02*

Note. Quadriceps and hamstrings surface electromyography normalized to maximum volitional isometric contraction and integrated through the landing phase. Development of co-contraction indices is taken from Rudolph (2001).
* Statistically significant difference between contact and non-contact groups at $P<0.05$

Table 3. Neuromuscular activation through the weight acceptance phase of a single leg landing. Descriptive statistics are reported as Mean(SD).

	Contact Group			Non-Contact Group		
Measure	Involved	Uninvolved	P	Involved	Uninvolved	P
Co-contraction Index	25.1 (9.3)	19.81 (8.0)	0.004*	30.3 (18.2)	24.42 (10.6)	0.07
Quadriceps	42.8 (16.0)	43.5 (15.7)	0.85	43.2 (13.5)	45.5 (15.6)	0.36
Hamstrings	24.3 (20.4)	16.7 (6.0)	0.06	23.5 (13.3)	20.9 (8.4)	0.31

Note. Quadriceps and hamstrings surface electromyography normalized to maximum volitional isometric contraction and integrated through the landing phase. Development of co-contraction indices is taken from Rudolph (2001).
* Statistically significant difference between contact and non-contact groups at $P<0.05$

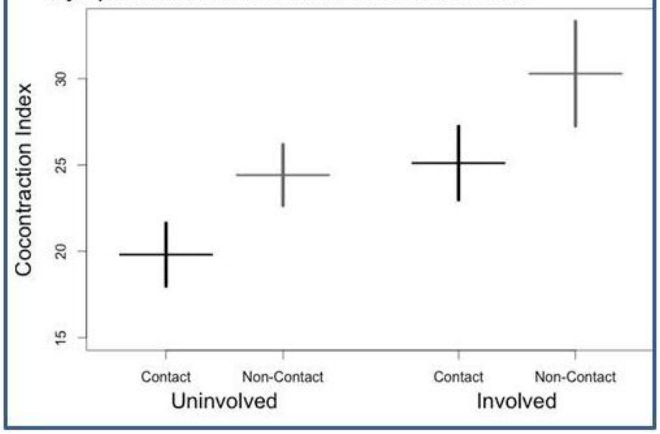
Results

Descriptive characteristics of the 55 subjects can be found in Table 1. Thirty-two were female; 23 were male. Nineteen had sustained contact injuries; 36 had non-contact injuries. Preferred sports most frequently included basketball, soccer, volleyball, and football. The average IKDC score of the entire cohort was 84.3±10.0 (mean±SD).

Neuromuscular

A significant difference was found in the CoI of the uninvolved limb between the contact and non-contact groups ($P = 0.04$), with an effect size of $d = 0.49$ (**FIGURE 2**). However, the difference between the contact and non-contact groups in the involved limb only approached significance ($P = 0.08$; $d = 0.35$; **TABLE 2**). A significant difference

Figure 2. Co-contraction index differences by mechanism of injury. Error bars are standard error of the mean.



between the involved and uninvolved limbs of the contact group, with an effect size of *d* = 0.61, was also found (*P* = 0.004; **TABLE 3**). In contrast, in the non-contact group the difference between the involved and uninvolved limbs again only approached significance (*P* = 0.07; *d* = 0.39). Further, there was no significant difference between the involved limb of the contact group and either limb of the non-contact group (*P* > 0.1).

Kinematics & Kinetics

There were no statistically significant differences between the contact and non-contact groups in any of the measured kinematic or kinetic variables (**TABLE 4**). However, in both groups the involved limb had significantly lower peak ankle dorsiflexion (*P* < 0.001) and peak knee moment (P< 0.001) compared to the uninvolved limb (**TABLE 5**). In the contact group, the involved limb had significantly lower peak knee flexion compared to the uninvolved limb (P=0.02).

Table 4. Differences in peak sagittal kinematic and kinetic measures between groups. Descriptive statistics are reported as Mean(SD).

	Involved Limb			Uninvolved Limb		
Measure	Contact	Non-contact	P	Contact	Non-contact	P
Hip flexion	49.1 (17.3)	46.8 (14.7)	0.63	47.2 (14.7)	45.7 (14.5)	0.72
Knee flexion	57.0 (13.1)	57.1 (11.5)	0.97	62.6 (13.6)	59.1 (10.3)	0.34
Ankle dorsiflexion	15.7 (6.1)	16.5 (5.6)	0.64	20.6 (5.3)	18.8 (4.9)	0.23
Hip moment	2.6 (0.8)	2.7 (0.6)	0.66	2.6 (0.7)	2.6 (0.8)	0.92
Knee moment	2.2 (0.5)	2.4 (0.5)	0.14	2.7 (0.4)	2.7 (0.5)	0.76
Ankle moment	2.1 (0.3)	2.2 (0.3)	0.45	2.1 (0.3)	2.2 (0.4)	0.42
VGRF[a]	3.6 (0.4)	3.6 (0.3)	0.85	3.7 (0.6)	3.7 (0.4)	0.84

[a] VGRF, vertical ground reaction force

Discussion

The purpose of the study was to examine the motor patterning of the quadriceps and hamstrings during single-leg landing following ACL reconstruction. People with a non-contact MoI tend to have higher co-contraction during a single leg landing as compared to people with a contact MoI, verifying our first hypothesis. The co-contraction index, our primary measure of interest, differed significantly between people with a contact versus a non-contact MoI on the non-surgical limb. The difference in co-contraction by MoI approached significance on the surgical limb. We also hypothesized an increase in co-contraction within the involved limb. A significant difference in co-contraction between the involved and un-involved limbs was found in the contact MoI group, and approached a significant difference in the non-contact MoI group. Interestingly, while there were consistent decreases in peak ankle angles and external knee moments on the involved limb, we did not find a significant difference in sagittal plane kinematic or kinetic measures between MoI groups.

Table 5. Differences in peak sagittal kinematic and kinetic measures between limbs. Descriptive statistics are reported as Mean(SD).

	Contact Group			Non-Contact Group		
Measure	Involved	Uninvolved	P	Involved	Uninvolved	P
Peak hip flexion	49.1 (17.3)	47.2 (14.7)	0.25	46.8 (14.7)	45.7 (14.5)	0.39
Peak knee flexion	57.0 (13.1)	62.6 (13.6)	0.02*	57.1 (11.5)	59.1 (10.3)	0.09
Peak ankle flexion	15.7 (6.1)	20.6 (5.3)	<0.001*	16.5 (5.6)	18.8 (4.9)	0.002*
Peak hip moment	2.6 (0.8)	2.6 (0.7)	0.80	2.7 (0.6)	2.6 (0.8)	0.29
Peak knee moment	2.2 (0.5)	2.7 (0.4)	<0.001*	2.4 (0.5)	2.7 (0.5)	<0.001*
Peak ankle moment	2.1 (0.3)	2.1 (0.3)	0.74	2.2 (0.3)	2.2 (0.4)	0.64
Peak VGRF[a]	3.6 (0.4)	3.7 (0.6)	0.21	3.6 (0.3)	3.7 (0.4)	0.14

[a] VGRF, vertical ground reaction force
* Statistically significant difference between involved and uninvolved side at $P<0.05$

The difference between the uninvolved limb of the contact group and both limbs of the non-contact group highlights the potential difference in neuromuscular behavior according to the mechanism of injury. In essence, the neuromuscular behavior profile of the uninvolved limb of a person with a non-contact injury mirrors that of the involved limb of a person with a contact injury. While the p-value of the difference between groups for the involved limb only approaches significance, the pattern shown in **FIGURE 2** suggests that injury and reconstruction to the limb of a person with a non-contact injury increases co-contraction beyond that of a person with a contact injury. Such a difference has potential implications for prognosis in rehabilitation.

The bilateral nature of greater co-contraction in both limbs of the non-contact MoI group suggests an intrinsic, central source of the difference in neuromuscular control that is present despite surgical correction of knee laxity. The results of the current study are consistent with findings demonstrating a decreased likelihood of pre-surgical coper status in those athletes with a non-contact MoI.[22] It is thought that copers are able to perform in high-intensity activities without the physical restraint of the ACL due to distinct neuromuscular coordination differences from non-copers, specifically decreased co-contraction of the hamstrings with the quadriceps.[23,35,36] The current results also suggest that reducing co-contraction is a preferred neuromuscular strategy to enhance dynamic control of the lower extremity joints, which might decrease the risk of second injury or osteoarthritis.

Co-contraction of the thigh musculature during landing may increase the risk of early-onset osteoarthritis of the knee, one of the most functionally debilitating long-term outcomes following ACL reconstruction, by increasing compression within the tibiofemoral joint.[12] While several other factors are involved, co-contraction is a modifiable risk factors for osteoarthritis following ACLR, and thus is ripe for intervention. Perturbation training after injury but before surgery has been found to both decrease co-contraction and increase the likelihood of people with ACL injury to attain coper status.[24] Instruction for increased knee flexion and softer landings during a single leg absorptive landing also decreases co-contraction in landing, thereby decreasing compression following ACL reconstruction.[25,26] The results of the current study underscore the importance of prioritizing landing retraining efforts during rehabilitation of athletes with non-contact MoI. Clinically, visually estimating knee bending during landing and listening for loudness of landing are the most convenient indicators of performance.[16,37] That there was no difference in peak knee flexion and VGRF between people with contact or non-contact injuries suggests that the movement patterns and performance would present similarly in the clinic. The neuromuscular differences between them may not be detectable without specialized EMG equipment. However, consideration of MoI and therefore potentially increased co-contraction may prioritize perturbation or plyometric training to ameliorate risk for secondary osteoarthritis as well as second injury risk reduction in return-to-sport rehabilitation.

The current study is a laboratory-based assessment, and habitual movement in sport may differ from that seen in the laboratory. While the validity of the findings may be compromised, at this time we currently do not have the means to collect EMG and kinetic data in the field. Further limitations lie within the cross-sectional design. Because of the higher prevalence of non-contact injury, there is a demographic difference in available subjects, which leads to the disparity in sample size between groups in the current study. Additionally, while a central mechanism is suggested for increased co-contraction in those athletes with a non-contact MoI, we cannot infer pre-injury co-contraction status from this study. The neuromuscular behaviors of the uninjured side could be affected by the injury, surgery, and rehabilitative process of the injured side. After ACL reconstruction, injury of the contralateral side is more common than re-injury of the surgical knee.[15] At this time, there is no research suggesting the phenomenon of increased contralateral injury risk differs by MoI.

Prospective longitudinal studies utilizing EMG as part of injury risk screening are therefore merited, to determine whether elevated co-contraction is present prior to non-contact injury, to determine whether elevated co-contraction following surgery increases re-injury or contralateral injury risk, and to determine whether elevated co-contraction following surgery increases the risk of early-onset knee osteoarthritis. However, such studies would require initial sample sizes in the thousands, a clear logistical challenge. However, given the possibility of poorer outcomes for those patients with non-contact injury, consideration of contact v. non-contact MoI is also warranted in further study into the long-term functional outcomes of ACL reconstruction.

Conclusions

Following ACL reconstruction, muscle activation patterns of the thigh musculature during sport simulated tasks differ depending on MoI. The increases in co-contraction occur bilaterally, suggesting a central source of neuromuscular coordination differences. Future studies of long-term postoperative return-to-sport, second ACL injury, and secondary knee OA development should include consideration of MoI, as there may be a differential outcome in those individuals who have a non-contact injury. Clinically, patients with a non-contact MoI may benefit from specific and bilateral perturbation or plyometric training to decrease further risk of early-onset knee osteoarthritis.

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References

1. Spindler KP, Wright RW. Clinical practice. Anterior cruciate ligament tear. *N Engl J Med.* 2008;359(20):2135-2142.
2. Beynnon BD, Johnson RJ, Abate JA, Fleming BC, Nichols CE. Treatment of anterior cruciate ligament injuries, part I. *Am J Sports Med.* 2005;33(10):1579-1602.
3. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538-543.
4. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med.* 2014;42(10):2363-2370.
5. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.
6. Myklebust G, Engebretsen L, Braekken IH, Skjolberg A, Olsen OE, Bahr R. Prevention of anterior cruciate ligament injuries in female team handball players: a prospective intervention study over three seasons. *Clin J Sport Med.* 2003;13(2):71-78.
7. Dai B, Herman D, Liu H, Garrett WE, Yu B. Prevention of ACL injury, part II: effects of ACL injury prevention programs on neuromuscular risk factors and injury rate. *Res Sports Med.* 2012;20(3-4):198-222.
8. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *J Biomech.* 2011;44(10):1845-1851.
9. Holm I, Oiestad BE, Risberg MA, Aune AK. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon-bone

autograft: a randomized study with 10-year follow-up. *Am J Sports Med.* 2010;38(3):448-454.

10. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *Am J Sports Med.* 2010;38(11):2201-2210.
11. Arokoski JP, Jurvelin JS, Vaatainen U, Helminen HJ. Normal and pathological adaptations of articular cartilage to joint loading. *Scand J Med Sci Sports.* 2000;10(4):186-198.
12. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
13. Shelbourne KD, Gray T, Haro M. Incidence of subsequent injury to either knee within 5 years after anterior cruciate ligament reconstruction with patellar tendon autograft. *Am J Sports Med.* 2009;37(2):246-251.
14. Barber-Westin SD, Noyes FR. Objective criteria for return to athletics after anterior cruciate ligament reconstruction and subsequent reinjury rates: a systematic review. *Phys Sportsmed.* 2011;39(3):100-110.
15. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.
16. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
17. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21(8):948-957.
18. Vairo GL, Myers JB, Sell TC, Fu FH, Harner CD, Lephart SM. Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(1):2-14.
19. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am J Sports Med.* 1988;16(2):113-122.
20. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9(2):62-71.
21. Chmielewski TL, Rudolph KS, Snyder-Mackler L. Development of dynamic knee stability after acute ACL injury. *J Electromyogr Kinesiol.* 2002;12(4):267-274.
22. Hurd WJ, Axe MJ, Snyder-Mackler L. Influence of age, gender, and injury mechanism on the development of dynamic knee stability after acute ACL rupture. *J Orthop Sports Phys Ther.* 2008;38(2):36-41.

23. Chmielewski TL, Hurd WJ, Snyder-Mackler L. Elucidation of a potentially destabilizing control strategy in ACL deficient non-copers. *J Electromyogr Kinesiol.* 2005;15(1):83-92.
24. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* 2005;85(8):740-749; discussion 750-744.
25. Elias AR, Hammill CD, Mizner RL. Changes in quadriceps and hamstring cocontraction following landing instruction in patients with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2015;45(4):273-280.
26. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
27. Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *Am J Sports Med.* 2009;37(5):890-897.
28. Ebrahimzadeh MH, Makhmalbaf H, Golhasani-Keshtan F, Rabani S, Birjandinejad A. The International Knee Documentation Committee (IKDC) Subjective Short Form: a validity and reliability study. *Knee Surg Sports Traumatol Arthrosc.* 2015;23(11):3163-3167.
29. Grevnerts HT, Terwee CB, Kvist J. The measurement properties of the IKDC-subjective knee form. *Knee Surg Sports Traumatol Arthrosc.* 2014.
30. Harty CM, DuPont CE, Chmielewski TL, Mizner RL. Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks. *Scand J Med Sci Sports.* 2011;21(1):98-105.
31. Kellis E, Arabatzi F, Papadopoulos C. Muscle co-activation around the knee in drop jumping using the co-contraction index. *J Electromyogr Kinesiol.* 2003;13(3):229-238.
32. Vos EJ, Harlaar J, van Ingen Schenau GJ. Electromechanical delay during knee extensor contractions. *Med Sci Sports Exerc.* 1991;23(10):1187-1193.
33. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
34. Zuur AF, Ieno EN, Elphick CS. A protocol for data exploration to avoid common statistical problems. *Methods Ecol Evol.* 2010;1(1):3-14.
35. Lentz TA, Tillman SM, Indelicato PA, Moser MW, George SZ, Chmielewski TL. Factors associated with function after anterior cruciate ligament reconstruction. *Sports Health.* 2009;1(1):47-53.
36. Lewek MD, Chmielewski TL, Risberg MA, Snyder-Mackler L. Dynamic knee stability after anterior cruciate ligament rupture. *Exerc Sport Sci Rev.* 2003;31(4):195-200.
37. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.

CHANGES IN QUADRICEPS AND HAMSTRING CO-CONTRACTION FOLLOWING LANDING INSTRUCTION IN PATIENTS WITH ACL RECONSTRUCTION

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STUDY DESIGN: Pre-test/post-test controlled laboratory study.

OBJECTIVES: To determine changes in the neuromuscular activation of the quadriceps and hamstrings following instructions aimed at improving knee flexion during a single-limb landing task in persons who have undergone anterior cruciate ligament reconstruction (ACLR).

BACKGROUND: Clinicians advise patients who have undergone ACLR to increase knee flexion during landing tasks to improve impact attenuation. Another long-standing construct underlying such instruction involves increasing co-contraction of the hamstrings with the quadriceps to limit anterior shear of the tibia on the femur. The current study examined whether co-contraction of the knee musculature changes following instruction to increase knee flexion during landing.

METHODS: Thirty-four physically active subjects with unilateral ACLR participated in a 1-time testing session. The kinetics and kinematics of single-leg landing on the surgical limb were analyzed before and after instruction to increase knee flexion and reduce the impact of landing. Vastus lateralis and biceps femoris activities were analyzed using surface electromyography and normalized to a maximal voluntary isometric contraction (MVIC). Co-contraction indices were integrated over the weight-acceptance phase of landing.

RESULTS: Following training, peak knee flexion increased (pre-instruction mean ± SD, pre: 56°±11°; post-instruction, 77°±12°; P<.001) and peak vertical ground reaction forces decreased (pre-instruction, 3.50±0.42 body mass; post-instruction, 3.06±0.44 body mass; P<.001). Co-contraction also decreased following instruction (pre-instruction, 30.88±17.68 %MVIC; post-instruction, 23.74±15.39 %MVIC; P<.001). The change in co-contraction was correlated with a decrease in hamstring activity (pre-instruction, 23.79±12.88 %MVIC, post-instruction, 19.72±13.92 %MVIC; r = 0.80, P<.001).

CONCLUSIONS: Landing instruction produced both a statistically and clinically significant change in landing mechanics in persons post-ACLR. Conscious improvement of the absorptive power of the surgical limb was marked by decreased hamstrings activity and co-contraction during single limb landing.

KEY WORDS: *biomechanics, EMG, knee, lower extremity, motor control/learning*

Most of the nearly 200,000 individuals who injure their anterior cruciate ligament (ACL) in the United States each year will undergo ACL reconstruction (ACLR).[1] Despite resolution of knee laxity and a relatively rapid return to physical activity,[2,3] a growing body of evidence suggests that these individuals avoid normal weight acceptance and force attenuation in their operative knee during high-demand activities.[4-7] Specifically, patients who have undergone ACLR have been reported to exhibit decreased peak knee flexion, decreased external knee flexion torque, and increased ground reaction forces during single-leg landing compared to healthy peers[7]. These differences also have been observed in the uninvolved side in persons with unilateral injury.[4]

Kinetic asymmetries during landing have been reported to be associated with poor long-term outcomes.[8] Fewer than 50% of patients who undergo ACLR return to their pre-injury performance levels 2 to 7 years postsurgery.[9,10] Patients also face a significantly increased risk of early-onset knee osteoarthritis, wherein over half of patients who undergo ACLR show radiographic evidence of osteoarthritis 10 to 15 years after surgery.[11]

The abnormal movement patterns observed post-ACLR appear amenable to training.[12,13] Recently published practice protocols have recommended training in landing as the final step of a return-to-sport rehabilitation program.[2,3] Interestingly, these protocols highlight discordant messages present in the literature on ACLR rehabilitation. While recommending similar general progressions of rehabilitation, the theories underlying each protocol are dichotomous with respect to the role of the hamstring musculature.

The hamstrings are described as one of the primary active restraints for anterior tibial translation during weight-bearing activities.[14] Renstrom et al[14] published a seminal cadaveric study that demonstrated the line of pull of the hamstrings as being parallel to and protective of the ACL at knee flexion angles greater than 30°. In a prospective study, female athletes who went on to sustain noncontact ACL injuries exhibited a higher ratio of quadriceps strength to hamstring strength when compared to matched uninjured male and female athletes.[15] This asymmetry in strength provides additional evidence that relative hamstring strength plays a role in ACL injury risk. The prevailing theoretical construct is that co-contraction of the hamstrings with the quadriceps is normal and a desirable outcome of ACLR rehabilitation.[16-19] For example, Hewett et al[3] recommend increasing co-contraction of the hamstrings and quadriceps during landing tasks.

However, research undertaken on healthy, well-trained jumping athletes has not conclusively shown elevated hamstring activity during landing.[20,21] It appears that in healthy populations, the knee absorbs large impact loads during jump-landing tasks through significant flexion and eccentric quadriceps activity, with relatively modest hamstring activity.[21-23] A recently published study by Tsai and Powers[13] found increased co-contraction of the ACLR knee in female athletes during a single-limb landing task compared to healthy peers. These authors also reported that these individuals exhibited elevated tibiofemoral compressive loads, possibly increasing the risk for premature osteoarthritis.[7] Interestingly, Tsai and Powers[13] found a reduction in co-contraction of the knee flexors and extensors and tibiofemoral joint compression following instruction for increased hip and knee flexion during the stretch-shortening cycle of single-leg hopping.

The findings of Tsai and Powers[35] complement work on the protective strategies used by ACL-deficient copers versus non-copers. In a series of studies, individuals who were able to return to high-demand tasks after ACL rupture without giving-way episodes (copers) used less co-contraction in physically challenging tasks than non-copers, who were defined as those who required surgery for knee joint stabilization.[5,24,25] Additionally, Chmielewski et al[26] reported that perturbation training in ACL deficient patients classified as “potential copers” resulted in a reduction in quadriceps-hamstring co-contraction while adapting movement patterns to more closely match research participants without injury (e.g., increased knee flexion during weight acceptance). Recently published post-operative clinical guidelines from the same laboratory offer no recommendations regarding hamstring strength as part of clinical milestones for treatment progression. [2] Instead, these authors advocated increasing quadriceps strength to within 90% of the contralateral side and incorporating sport-specific perturbation training and jump training into late-stage rehabilitation, with the goal of increasing knee flexion.

Clinicians may be understandably confused by the apparently disparate, yet equally compelling, emphases on hamstring muscle activity during dynamic activities.

Such dichotomy in the literature may manifest in an inappropriate preference for muscle strengthening or targeted muscle activation patterning during landing, which limits athletes from efficient achievement of their goals.

The purpose of the current study was to examine training-induced changes in quadriceps and hamstring muscle activity following instruction for what has been reported as a preferred strategy for impact attenuation during a single-leg landing task in persons who have undergone ACLR. Previous studies have examined muscle activity during gait and countermovement tasks in female athletes. Neuromuscular demands may differ between countermovement tasks, which require elastic return of potential energy, and landing tasks, in which ground reaction forces are fully absorbed by the musculoskeletal system. The neuromuscular responses to single-leg landings have not been fully explored. In addition, the response of male athletes to landing training post-ACLR has not been examined. This is important, as augmenting knee flexion during landing appears to decrease tension on the ACL,[27] whereas landing with limited knee flexion appears to be a significant risk factor for ACL injury.[28] We hypothesized that (1) landing performance of the ACLR knee would improve following instruction in landing technique, as evident by an increase in knee flexion and knee extensor moment and decreased peak vertical ground reaction forces (VGRFs) compared to pre-instruction values; and that (2) co-contraction of the quadriceps and hamstrings would decrease, with a concomitant reduction in overall hamstring recruitment and an increase in quadriceps recruitment.

Table 1. Participant characteristics of 34 subjects with unilateral ACL reconstruction. Age, BMI, Date of Surgery, and IKDC score are reported as Mean(SD).

Participant Characteristics		
	Mean (Standard Deviation)	Range
Age	21.9 (4.5) years	15 – 34 years
BMI	23.8 (2.6)	20.5 – 34.1
Date of Surgery	23.6 (14) months prior	6 – 48 months prior
Current IKDC Score	85.9 (8.8) %	68 – 98 %
Sex	20 Female	14 Male
Mechanism of Injury	26 Non-Contact	8 Contact
Concomitant Injury	25 Meniscal Injuries	2 MCL Injuries
	2 Meniscectomy/Debridement	
	7 Meniscal Repair	
Graft Type	Primary	Revision
	25 Hamstring	3 BPTB
		2 Contralateral Hamstring
		1 Cadaveric Allograft
	9 BPTB	1 Cadaveric Allograft
	6 Cadaveric Allograft	

Abbreviations: ACL, anterior cruciate ligament; BMI, body mass index; IKDC, International Knee Documentation Committee questionnaire; BPTB, bone-patellar tendon-bone autograft; MCL, medial collateral ligament

METHODS

Subjects

Twenty female and 14 male athletes were recruited from a population of 12 – 35-

year-old recreational and competitive athletes who had undergone ACLR between 6 and 48 months previously. All athletes had returned to recreational activity (**TABLE 1**). Preferred sports included basketball (10 subjects), alpine skiing (3 subjects), soccer (9 subjects), volleyball (2 subjects), football (3 subjects), and other (7 subjects). Surgical procedures varied and are detailed in **TABLE 1**. Subjects were excluded if they had (1) more than 2 ACLR surgeries on the same leg or ACL injuries in both knees, (2) a history of a posterior cruciate ligament injury, (3) a lower extremity or trunk injury that prevented normal activities of daily living within the previous 6 months, or (4) a Tegner Activity Scale score less than 4. The Tegner scale is a validated tool used to describe physical activity level in persons with ACLR.[29] All subjects provided signed informed consent, and the study was approved by the University of Montana Institutional Review Board.

Testing Protocol

Prior to testing, subjects completed the International Knee Documentation Committee Subjective Knee Form (IKDC) as a measure of subjective function.[9] Testing consisted of, in order, a 5-minute treadmill-walking warm-up, surface electromyography (EMG) electrode placement, maximal voluntary isometric contraction (MVIC) testing of the knee flexors and extensors, placement of reflective markers, standing kinematic data calibration, and biomechanical assessment of a single-leg landing task. This was followed by a brief instruction in landing technique, followed by biomechanical re-assessment of the single-leg landing task.

Single-Leg Landing Task

We chose a single-leg landing task[30] because the mechanism of a noncontact ACL injury typically occurs during single-leg impact.[28] Subjects performed 5 successful test trials of a single-leg landing task following at least 5, but no more than 10, practice repetitions for task familiarization. Subjects stood approximately 10 cm from the edge of a 20-cm box with their hands on their hips, and were instructed to gain their balance on a single leg before hopping forward off the box with their eyes looking forward. A trial was deemed successful if the subject maintained single-leg stance for at least 2 seconds upon landing and regaining the dual-leg stance in a controlled manner.

Motion Analysis

Kinematic data were obtained during the single-leg landing task using an 8-camera Vicon Nexus system at 200 Hz (OMG plc, Oxford, UK). Retroreflective markers (14-mm diameter) were placed on bilateral landmarks to identify the joint centers of the ankle, knee, and hip, as well as the top of the iliac crest to define the pelvis (**FIGURE 1**). Rigid thermoplastic shells with 4 markers affixed to their surfaces were attached bilaterally to the shank and thigh using elastic wraps (SuperWrap; Fabrifoam Products, Exton, PA). This allowed tracking of the 3-D position of each segment. A shell was also affixed over the sacrum to track the pelvis. Four markers placed on the superior and inferior heel counters of the shoe and the first and fifth metatarsal heads tracked foot movement. A standing calibration was performed prior to completing the landing trials to identify joint centers with respect to each segment's coordinate system. Joint center anatomical markers were then removed, with the shells indicating position of the aforementioned segments throughout testing.

Figure 1. Marker placement for biomechanical assessment.

A 400 x 600-mm force plate (Advanced Medical Technology, Inc, Watertown, MA) interfaced with the Vicon Nexus system captured ground reaction forces during landing. Force plate data were sampled at 1200 Hz. Marker trajectories and force plate data were respectively low-pass filtered at 12 and 50 Hz with fourth-order, phase-corrected Butterworth filters. The peak VGRFs and joint moments were normalized to each individual's body mass. Joint kinematics were calculated using Euler angles, and joint moments (internal) were calculated with inverse dynamics, using rigid-body analysis through custom applications with Visual 3D version 4.75.29 software (C-motion

Inc., Germantown, MD). All data were time normalized to 100 increments, from 150 milliseconds prior to initial contact on the force plate[21,31,32] to peak knee flexion during landing (the weight-acceptance phase), to enable the calculation of an ensemble average across trials for each subject, as the time between these events varied slightly within subject trials.

Muscle activation levels were recorded from the vastus lateralis and biceps femoris,[25] using a Bagnoli surface EMG system (Delsys Inc, Natick, MA) interfaced with the Vicon Nexus system with a 16-bit analog-digital converter. Differential surface electrodes, with 10 x 1 mm diameter silver bar contacts, spaced at a distance of 10 mm, were placed at the mid muscle belly and oriented parallel to the muscle fibers, taped in place, and wrapped with elastic wraps to ensure minimal movement artifact. The skin was cleaned with alcohol prior to placement. The electrode common-mode rejection ratio was 92 dB, and the system noise was less than 1.2 µV.

Electromyographic signals were preamplified at the interface, amplified at the system level with a gain of 1000, and sampled at 1200 Hz. Using Visual3D software, signals were band-pass filtered at 20 to 350 Hz and full-wave rectified before a linear envelope was created with a 10-Hz, low-pass, phase corrected Butterworth filter. Knee flexor and extensor maximal voluntary isometric contractions were performed using a Kin-Com 125AP dynamometer (Isokinetic International, Harrison, TN) utilizing previously published methods.[12,33] Patients were seated and secured in place, with the knee positioned in 90° and 60° of knee flexion for knee extension and knee flexion testing, respectively. Peak muscle activation levels during the trial with the greatest torque production were recorded and used for normalization purposes.

Co-contraction and a co-contraction index were calculated according to the method used by Rudolph et al,[25] which combines estimations of the magnitude of co-contraction as well as relative activity. Instantaneous co-contraction was defined as the weighted ratio between instantaneous hamstring and quadriceps activation. The co-contraction index was defined as the integral of that function across the weight-acceptance phase of landing:

$$\int_{100\ ms\ before\ land}^{Peak\ knee\ flex} \frac{EMG_L}{EMG_H} * (EMG_L + EMG_H)$$

where *EMGL* is the normalized activation level of the less active muscle and *EMGH* is the normalized activation level of the more active muscle. Maximal quadriceps and hamstring activations during the weight acceptance phase were recorded. Additionally, the quadriceps and hamstring instantaneous activations were respectively integrated over the weight acceptance phase.

Landing Instruction

After completing the first set of single-leg landing trials, subjects were given a brief set of verbal landing instructions based on prior publications by Hewett et al[34] and McNair et al.[35] The scripted instructions asked the subjects to land as softly and quietly as possible by hitting toes first and bending their knees during landing. Participants were instructed to keep their chest over their knees and their knees over their toes during landing. The investigator demonstrated poor landing technique, which included limited knee flexion and an abrupt halt to the weight-acceptance phase of landing. The demonstration was followed immediately by a demonstration of the desired technique, with accentuated knee flexion to absorb impact forces. Verbal and visual instruction was followed by a period of blocked practice that did not exceed 5 minutes. During this time, subjects performed at least 6 practice trials. Verbal feedback was provided to reinforce a quiet landing and increased knee bending. After the practice period,

Table 2. Peak kinematic and kinetic data with muscular activation changes following instruction for improved landing. Measures are reported as Mean(SD). Cohen's *d* is used as a measure of effect size.

Kinematics	Pre-training	Post-training	Effect Size		p-value
Hip Flexion	46.1±15.4°	66.1±15.6°	1.29	*	0.000
Knee Flexion	56.0±11.3°	77.2±12.2°	1.81	*	0.000
Ankle Dorsiflexion	14.9±4.9°	22.6±5.5°	1.47	*	0.000
Kinetics					
VGRF	3.50±0.42	3.06±0.44	1.13	*	0.000
Hip Extension Moment	2.59±0.58	2.45±0.55	0.24		0.162
Knee Extension Moment	2.46±0.41	2.51±0.38	0.12		0.225
Ankle Plantar flexion Moment	2.16±0.29	1.99±0.23	0.65	*	0.000
EMG (% MVIC)					
Co-contraction Index	30.88±17.68	23.74±15.39	0.45	*	0.000
Co-contraction Max	0.74±0.37	0.64±0.36	0.30	*	0.002
Quadriceps Activation	43.61±14.47	44.44±15.09	0.05		0.275
Quadriceps Max	0.86±0.31	0.88±0.29	0.03		0.247
Hamstring Activation	23.79±12.88	19.72±13.92	0.32	*	0.000
Hamstring Max	0.47±0.21	0.46±0.27	0.09		0.314

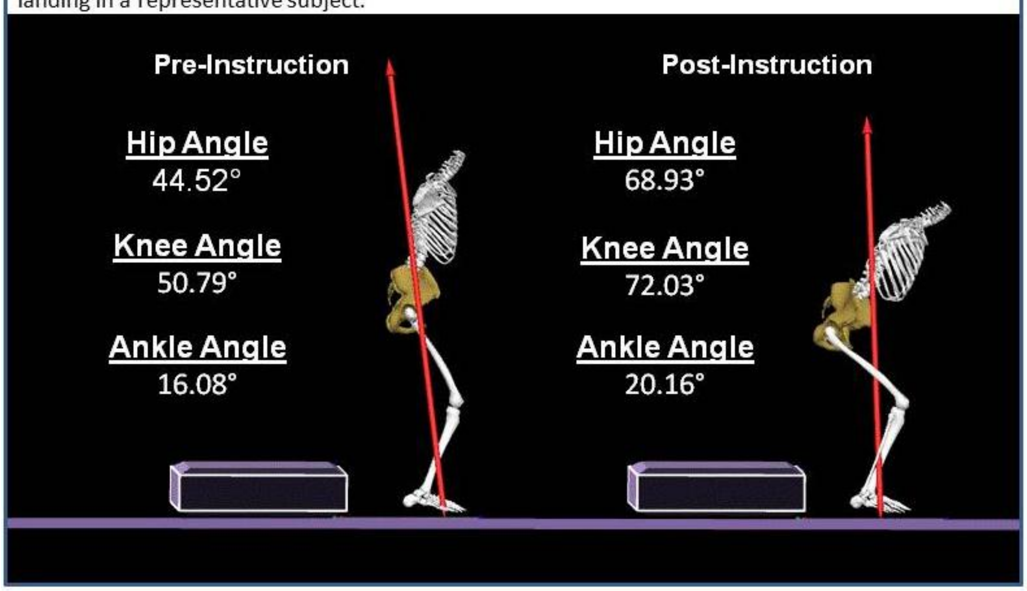
Abbreviations: VGRF, vertical ground reaction force; EMG, electromyography; MVIC, maximum voluntary isometric contraction; SD, standard deviation; BM, body mass.
VGRF normalized and reported as a ratio of body mass; Moments reported as N·m/kg of body mass; EMG activation levels normalized to MVIC and reported as % of MVIC.
* Indicates a significant difference between pre-and post-instruction at $P \leq 0.05$

another 5 successful trials (as defined above) of single-leg landing on the operative leg were recorded.

Data Analysis

Descriptive statistics were prepared for all variables of interest. Quantile-quantile plots confirmed normality and equal variance assumptions for statistical testing, and no significant outliers were found. Kinematic and kinetic changes (peak VGRF, peak knee flexion, and peak knee extensor moment) taken before and after instruction were compared using paired *t* tests. Ankle and hip kinematics and kinetics were also examined as a preliminary assessment of instruction on global lower extremity function. Paired *t* tests also were used to compare pre-instruction and post-instruction co-contraction indices, as well as means of both peak and integrated normalized quadriceps and hamstring activity, providing measures of peak and overall demand, respectively. Cohen *d* was generated as a measure of effect size for all variables of interest. Pearson correlation coefficients were generated to estimate the strength of the relationships between the change in co-contraction index and the change in either hamstring or quadriceps activity. Statistical tests were performed with SPSS Statistics Version 20.0 (IBM Corporation, Armonk, NY) with an alpha-level set to $P \leq 0.05$.

Figure 2. Kinematic and kinetic changes at peak knee flexion following instruction for improved landing in a representative subject.



RESULTS

Kinematic, kinetic, muscle activity, and muscle strength data are reported in **TABLE 2**. Every subject displayed an increase in ankle, knee, and hip joint flexion following training (**FIGURE 2**). On average, peak knee flexion increased by 38% (95% confidence interval (CI): 32.8%, 47.9%; *P*<0.001), peak hip flexion increased by 43% (95% CI: 39.5%, 60.3%; *P*<0.001), and peak ankle dorsiflexion increased by 51% (95% CI: 44.5%, 75.3%; *P*<0.001). Mean VGRF in landing decreased by 13% following training (95% CI: 8.3%, 14.8%; *P*<0.001). There was no significant change in peak knee or hip extensor moment (knee 95% CI: -6.31%, 0.69%; hip 95% CI: -2.84%, 9.46%; *P*>0.05), though the 8% change in ankle moment was significant (95% CI: 4.6%, 10.2%; P<0.001). Prior to instruction, the weight-acceptance phase averaged 0.35 ± 0.07 seconds; following instruction, this time

Figure 3. Co-contraction index change for all subjects following instruction for improved landing. Mean indicated by bold line.

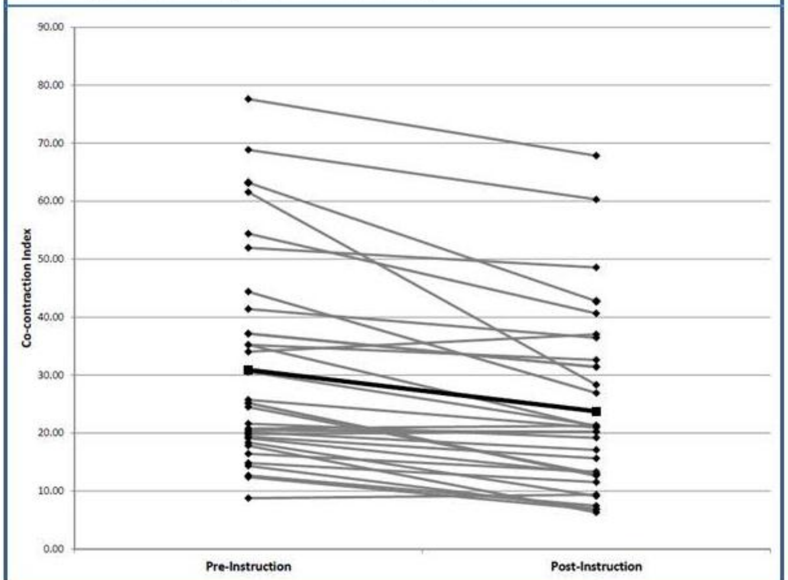
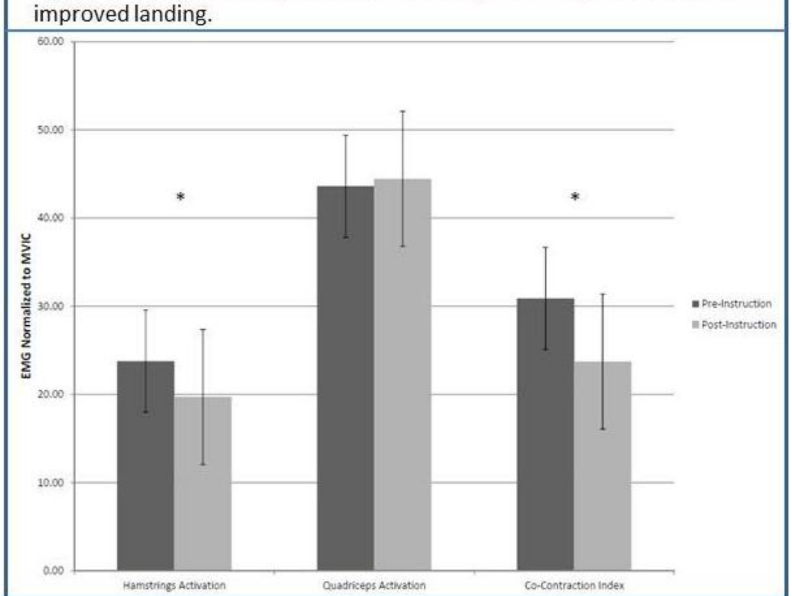


Figure 4. Changes in integrated muscle activity following instruction for improved landing.



Abbreviations: EMG, electromyography; MVIC, maximal voluntary isometric contraction
* Indicates a significant difference between pre- and post-instruction at *P*≤0.05

period averaged 0.53 ± 0.12 seconds.

The co-contraction index decreased by 24% following instruction (95% CI: 17.8%, 31.9%; $P<0.001$) (**FIGURES 3** and **4**). There was also an 18% significant decrease in integrated hamstring activity (95% CI: 11.7%, 27.7%; $P<0.001$) (**FIGURE 4**). Hamstring activity was found to be correlated with the CI ($r = 0.80$, $P<0.001$), as was the nonsignificant 2% increase in integrated quadriceps activity ($r = 0.34$, $P<0.05$). Maximal instantaneous co-contraction also decreased 15% with instruction (95% CI: 7.0%, 23.8%; $P<0.05$), though neither maximum hamstrings nor maximal quadriceps activity decreased significantly (hamstrings 95% CI: -5.4%, 19.4%; quadriceps 95% CI: -13.1%, 7.0%; $P>0.05$).

DISCUSSION

The primary results of our study revealed improved performance in landing kinematics and kinetics following instruction and changes in muscular activity. Short bouts of instruction have previously been reported to change landing mechanics in both healthy and injured populations, [13,35,36] and our brief instruction session also affected landing performance. To consciously accomplish a soft landing task, subjects significantly increased peak knee flexion and lowered peak ground reaction forces. Interestingly, the change in knee kinematics and ground reaction forces did not affect the peak knee extensor moment.

The mechanical changes induced by instruction for a softer landing were accompanied by a substantial modification of the neuromuscular activity of the quadriceps and hamstring muscles. In support of our hypothesis, co-contraction of the quadriceps and hamstrings decreased in all but 4 subjects, with a mean difference of 27%. These results are consistent with recent studies demonstrating decreased co-contraction with instruction for improved landing in both healthy and injured populations. Co-contraction levels dropped 43% when healthy athletes were trained in single-leg landings from at 10.5-cm box using a 0°-to-25° knee flexion target first and then advancing to a 50°-to-75° target knee flexion range.[23] Finally, Tsai and Powers[13] reported that co-contraction decreased by 36% following training for increased knee bending during the countermovement phase of a single-leg drop-vertical hop in females with ACLR. The tendency of decreasing co-contraction with increasing knee flexion holds true in lower-intensity tasks (ie, gait) as well.[5,25] Furthermore, perturbation training following acute ACL injury in potential copers induces decreased co-contraction and increased knee flexion in normal and disturbed walking tasks.[20,26]

The change in muscle activity also involved relative maintenance of both maximum and integrated quadriceps activation, with a significant decrease in integrated hamstrings activity. The hamstrings may not contribute to knee flexion throughout controlled landing tasks, as long as the quadriceps allows eccentric knee flexion. Podraza and White[23] also describe a decrease in hamstring activity with increased knee flexion in landing, though the EMG signals were converted to muscle moments in their analysis. [23] The hamstrings also play a role in the control of hip flexion, but we did not see an increase in hamstring activity corresponding to the increased hip flexion in landing.

There was no statistically significant increase in quadriceps activity post-training. With increased knee flexion, the entire center of mass lowers and maintains vertically above the center of pressure, requiring modulations in moment and concomitant muscular activation around all 3 primary lower extremity joints. The details of these modulations remain controversial.[37,38] Indeed, our sample of muscles was limited, and other muscle groups likely play an important role in the controlled lowering of the lower extremity. Tsai and Powers[13] argue that increasing hip and knee flexion may reduce external knee flexion torque, thereby decreasing demand on the quadriceps and hamstrings and potentially increasing reliance on the single joint hip extensors (gluteals) and ankle plantarflexors (soleus) as decelerators. In contrast, we found maintenance of knee moment, as well as hip moment, from which we can infer the demand on the quadriceps did not change. This is supported by our EMG results. Additionally, Podraza and White[23] found little change in soleus activity during similar landing adaptation .

The current investigation provides data that may clarify the confusion surrounding the role of the hamstrings and quadriceps activation during safe landing strategies post-ACLR. Our results suggest that providing patients with cues for co-contraction of the quadriceps and hamstrings with jump training is inconsistent with adaptations that occur with desired landing modifications. Furthermore, instruction to increase knee flexion in a landing task softens the impact forces while decreasing co-contraction, with an associated reduction in hamstring activity.

It must be noted that causal inferences cannot be made based on the results of this study. Furthermore, technique changes are outside each subject's standard motor plan; the activity patterns seen in this study represent motor adaptation rather than motor learning. The changes in muscle activity patterns that may occur with increasing task familiarity may be quite different and are the subject of future investigation. Additionally, subjects were rather heterogeneous, consisting of both males and females with varied injury mechanisms and surgical types. While these factors may be seen as potentially confounding variables, the strength of our results across a relatively heterogeneous population implies universality to the effects of surgery and training,[39] and in fact allows a broader applicability than would otherwise be possible.

CONCLUSIONS

Co-contraction between the quadriceps and hamstrings was found to decrease with improved single-leg landing in subjects with ACLR. Reduced co-contraction was primarily correlated with a decrease in hamstring activation, whereas quadriceps activity remained relatively consistent after landing instruction. Subjects were able to substantially change their landing technique with brief instruction, but it is unknown how these neuromuscular effects will change with prolonged training. While current rehabilitation protocols appropriately advocate for training patients to increase knee flexion during weight acceptance when landing, our findings suggest that the changes with instruction will not induce increased hamstring activity or a corresponding increase in quadriceps-to-hamstring co-contraction.

Key Points

Findings: Co-contraction between the quadriceps and hamstrings was found to decrease when adopting a single-leg landing technique with increased joint flexion and a softened landing in persons who have undergone ACLR. Decreased co-contraction was associated with reduced hamstring activity.

Implications: Short-term instruction can successfully change landing performance to induce increased knee flexion, enhance impact attenuation, and limit muscle co-contraction in persons post-ACLR.

Caution: Causality in the relationships between knee flexion, co-contraction, and hamstrings activity cannot be inferred from this study. The subject pool for this study involved a heterogeneous population. Additionally, immediate changes in technique and neuromuscular coordination were seen as a result of a single training session. The long-term effects of training are unclear.

REFERENCES

1. Cimino F, Volk BS, Setter D. Anterior cruciate ligament injury: diagnosis, management, and prevention. *Am Fam Physician.* 2010;82(8):917-922.
2. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.
3. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
4. Gauffin H, Tropp H. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med.* 1992;20(2):182-192.
5. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998;8(6):349-362.
6. Schmitt LC, Paterno MV, Hewett TE. The impact of quadriceps femoris strength asymmetry on functional performance at return to sport following anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2012;42(9):750-759.
7. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
8. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.
9. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538-543.

10. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2012;40(1):41-48.
11. Meuffels DE, Favejee MM, Vissers MM, Heijboer MP, Reijman M, Verhaar JA. Ten year follow-up study comparing conservative versus operative treatment of anterior cruciate ligament ruptures. A matched-pair analysis of high level athletes. *Br J Sports Med.* 2009;43(5):347-351.
12. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
13. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
14. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH. Strain within the anterior cruciate ligament during hamstring and quadriceps activity. *Am J Sports Med.* 1986;14(1):83-87.
15. Myer GD, Ford KR, Barber Foss KD, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med.* 2009;19(1):3-8.
16. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* 1987;15(3):207-213.
17. Baratta R, Solomonow M, Zhou BH, Letson D, Chuinard R, D'Ambrosia R. Muscular coactivation. The role of the antagonist musculature in maintaining knee stability. *Am J Sports Med.* 1988;16(2):113-122.
18. Hirokawa S, Solomonow M, Lu Y, Lou ZP, D'Ambrosia R. Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. *Am J Sports Med.* 1992;20(3):299-306.
19. Withrow TJ, Huston LJ, Wojtys EM, Ashton-Miller JA. Effect of varying hamstring tension on anterior cruciate ligament strain during in vitro impulsive knee flexion and compression loading. *J Bone Joint Surg Am.* 2008;90(4):815-823.
20. Hurd WJ, Chmielewski TL, Snyder-Mackler L. Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(1):60-69.
21. Kellis E, Arabatzi F, Papadopoulos C. Muscle co-activation around the knee in drop jumping using the co-contraction index. *J Electromyogr Kinesiol.* 2003;13(3):229-238.
22. Ford KR, Myer GD, Schmitt LC, Uhl TL, Hewett TE. Preferential quadriceps activation in female athletes with incremental increases in landing intensity. *J Appl Biomech.* 2011;27(3):215-222.
23. Podraza JT, White SC. Effect of knee flexion angle on ground reaction forces, knee moments and muscle co-contraction during an impact-like deceleration landing: implications for the non-contact mechanism of ACL injury. *Knee.* 2010;17(4):291-295.

24. Rudolph KS, Axe MJ, Snyder-Mackler L. Dynamic stability after ACL injury: who can hop? *Knee Surg Sports Traumatol Arthrosc.* 2000;8(5):262-269.
25. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9(2):62-71.
26. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* 2005;85(8):740-749; discussion 750-744.
27. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *J Biomech.* 2011;44(10):1845-1851.
28. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.
29. Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *Am J Sports Med.* 2009;37(5):890-897.
30. Harty CM, DuPont CE, Chmielewski TL, Mizner RL. Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks. *Scand J Med Sci Sports.* 2011;21(1):98-105.
31. Vairo GL, Myers JB, Sell TC, Fu FH, Harner CD, Lephart SM. Neuromuscular and biomechanical landing performance subsequent to ipsilateral semitendinosus and gracilis autograft anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2008;16(1):2-14.
32. Vos EJ, Harlaar J, van Ingen Schenau GJ. Electromechanical delay during knee extensor contractions. *Med Sci Sports Exerc.* 1991;23(10):1187-1193.
33. Davidson BS, Judd DL, Thomas AC, Mizner RL, Eckhoff DG, Stevens-Lapsley JE. Muscle activation and coactivation during five-time-sit-to-stand movement in patients undergoing total knee arthroplasty. *J Electromyogr Kinesiol.* 2013;23(6):1485-1493.
34. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.
35. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. *Br J Sports Med.* 2000;34(4):293-296.
36. Milner CE, Fairbrother JT, Srivatsan A, Zhang S. Simple verbal instruction improves knee biomechanics during landing in female athletes. *Knee.* 2012;19(4):399-403.
37. Heiderscheit BC. Lower extremity injuries: is it just about hip strength? *J Orthop Sports Phys Ther.* 2010;40(2):39-41.
38. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther.* 2010;40(2):42-51.

39. Campbell DT. *Experimental and Quasi-Experimental Designs for Research.* Boston, MA: Houghton Miffling Company; 1963.

THE EFFECT OF BODY WEIGHT SUPPORT ON KINETICS AND KINEMATICS OF A REPETITIVE PLYOMETRIC TASK

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Though essential to athletic performance, the ability to land from a jump often remains limited following injury. While recommended, jump training is difficult to include in rehabilitation programs due to inherently high impact forces. Body weight support (BWS) is frequently used in rehabilitation of gait following neurological and orthopedic injury, and may also allow improved rehabilitation of high-impact tasks. There is a differential effect of BWS on walking and running gaits, and the effect of BWS on movements with relatively large vertical displacement is unknown. The current study evaluates the effect of BWS on a replicable single leg hopping task. We posited that progressive BWS would decrease limb loading while maintaining the joint kinematics of the task. Twenty-eight participants repetitively hopped on and off a box at each of four BWS levels. Peak vertical ground reaction forces decreased by 22.5% between 0% and 30% BWS ($P<.001$). Average hip, knee, and ankle internal moments decreased by 0.5 BW each. Kinematics remained consistent across BWS levels ($P\leq.05$). The high level of task specificity evidenced by consistent kinematics coupled with a similar reduction of internal moment at each joint suggests that BWS may be a useful strategy for rehabilitation of jumping tasks.

Key Words: *body weight support, single leg hop, rehabilitation, plyometrics*

Body weight support (BWS) plays an important role in motor learning during retraining following both neurological and orthopedic injuries. A recent Cochrane Review found early ambulation training following stroke with BWS, either over ground or on a treadmill, improved gait speed and efficiency.[1] By providing task specific practice with graded intensity, BWS training improved bilateral coordination and gait symmetry in patients with chronic stroke.[2] Similar results have been found following incomplete spinal cord injury.[3,4] Evidence for use of BWS in orthopedic patient populations is limited, but several recent case reports have described success utilizing BWS to minimize exposure to physical stress during functional training while in the acute recovery stage following lumbar disk herniation,[5] Achilles tendon repair,[6] and multiple lower extremity fractures.[7]

While BWS is primarily used during tasks with a narrow variance of translation of a participant's center of mass, such as walking on a treadmill, BWS may also be effective for early retraining of tasks that require more dynamic movements involving sizable changes in vertical and horizontal position such as hopping or jumping. Such BWS could be particularly helpful for retraining patients following injuries or surgeries involving ligament reconstruction or cartilage repair. Athletes returning to jumping, landing, and other high-impact activities after knee surgeries, such as ACL reconstruction, frequently display abnormal landing mechanics and concomitant increased joint compression.[8] Chmielewski et al[9] found increased concentration of cartilage degradation markers in the first 16 weeks following ACL reconstruction and early knee osteoarthritis has been reported in up to 48% of patients 10 to 15 years following ACL reconstruction.[10] The neuromuscular impairments underlying the performance deficits in jump landing that may lead to cartilaginous degradation can be transiently affected by instruction.[11,12] Additional benefits of jump or plyometric training may include greater stimulation of Golgi tendon organs and muscle spindles.[13] The resulting enhancement of length feedback and force feedback reflex mechanisms may improve coordination and neuromuscular control.[14] As such, jump or plyometric training is consistently recommended in end-stage rehabilitation programs.[15,16] The increased risk of injury in single leg decelerations and rapid changes of direction[17,18] makes rehabilitation of single leg landing tasks particularly important.

Putting recommendations for plyometric training after injury into practice may be problematic, however. Plyometric exercise has been defined as activity which utilizes the stretch-shortening cycle to increase efficiency of force production or performance.[14] Examples include drop vertical jumps, in which an athlete drops off a box and immediately jumps into the air upon landing. A continuous transition between the eccentric control of landing and concentric push from the ground is necessary to take advantage of the elastic energy stored during the stretch-shortening cycle.[14] However, the high joint loads intrinsic to plyometric training[19] necessitate low repetition to avoid injury, a situation unfavorable toward motor learning.[20] As in gait retraining following neurological injury, BWS may allow increased repetition of plyometric tasks by mitigating large impact loads, thereby inducing improved carryover to daily tasks and activities.

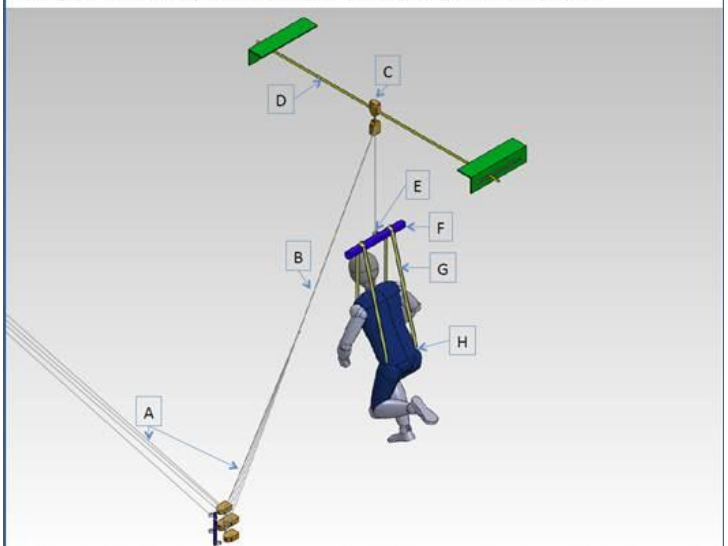
In order to be viable as a treatment strategy for plyometric tasks, BWS must decrease ground reaction forces and loading through the kinetic chain while maintaining the relative loading relationships between joints during large multi-planar excursions of the center of mass. In walking and running, the dose of BWS can modify the kinematics and efficiency of a patient's typical gait pattern, particularly at high levels of BWS.[21] The mechanical effect of reducing gravitational forces via BWS during plyometric activities is unknown.[22] Ackermann and van den Bogart[23] found profound changes in locomotion strategy while simulating gait in gravitational conditions mimicking those on Mars (g=3.72 m/s2) and the Moon (g=1.63 m/s2), with skipping preferred for its efficiency. Donelan and Kram[22] found that the effect on mechanics of reducing gravity is different for gaits utilizing elastic motion (running) versus pendular motion (walking). It is unknown whether plyometric activities such as hopping and jumping will respond similarly.

Thus, our objective in this study is to examine the effects of instruction and progressive BWS on the mechanical characteristics of a repetitive single leg plyometric task. The current study was designed to provide preliminary results to evaluate the potential of BWS as a therapeutic adjunct during retraining of dynamic tasks like plyometric training. We hypothesize that as BWS increases, overall ground reaction forces (GRF) and joint moments will progressively decrease, while kinematics will remain unchanged, thereby preserving the task specificity of training.

METHODS

BWS System

Figure 1 Illustration of Body Weight Support System with Harness



A, 15 m elastic tubes stretched over approximately 76 m around pulleys, redirected upward toward final pulleys. B, final elastic element to which appropriate tubes (A) may be attached. C, final conjoined pulleys. D, 2.44 m tensioned steel rod upon which top pulley of (C) can roll. E, 57 g analog load cell, sampled at 1200 Hz. F, hollow core aluminum yoke. G, free-sliding webbing. H, 3 mm neoprene shorts customized to allow movement without sliding.

The BWS system (**FIGURE 1**) consists of an array of long elastic rubber tubes with graduated spring constants strung in parallel through a system of pulleys. These tubes are attached to a single thick elastic element that is drawn through a final conjoined double pulley. One part of the conjoined pulley tracks along a tensioned 2.44 m steel tube that is suspended from the ceiling 3 m from the ground in an orientation that is orthogonal to the tube array. A second pulley is suspended from the first, and redirects the thick elastic element to culminate on an aluminum yoke. A harness of customized neoprene shorts attaches to the yoke with nylon strapping, which slides freely thereby allowing trunk motion. The system provides near constant vertical force at the center of mass of the participant while they move within the 0.5 x .05 x 1 m volume used to complete the box hop task. A small, lightweight (57 g) analog load cell (Futek, Inc., Irvine, CA) placed inline where the tube attaches to the yoke allowed precise titration of the vertical force. The maximum vertical force allowed by the system was 90 pounds. We sampled at 1200 Hz throughout each trial to determine the variability of load during the box hops task. The difference between the maximal and minimal vertical forces, or load variability, was expressed as a ratio of the target force by the following equation:

$$\frac{||F_{max} - F_{min}||}{F_t}$$

where F_t is the target vertical force, F_{max} is the maximal force observed, and F_{min} is the minimal force observed within a single trial.

Participants

Thirteen male and fifteen female athletes were recruited from a population of healthy, active adults (**TABLE 1**). Participants were excluded if they had a history of lower extremity or back injury that had limited their activities of daily living in the past (e.g., fracture) or if they had a Tegner Activity Scale score <4. The Tegner Scale is a tool used to describe activity levels that has been validated in prior studies of people with ACLR,[24] as well as in populations with uninjured knees.[25] In order to provide the maximal target dose of BWS (30%), participants were also excluded if their weight exceeded 300 pounds. All participants provided signed informed consent as provided by the University of Montana Institutional Review Board.

Table 1 Descriptive characteristics of participants, mean (SD)

	Males (n = 13)	Females (n = 15)
Age (years)	24.15 ± 4.18	24.93 ± 2.52
Tegner Scale Score	7.15 ± 1.28	6.60 ± 0.63
BMI	24.27 ± 2.29	21.9 ± 1.79
Height (m)	1.8 ± 0.08	1.7 ± 0.03
Weight (kg)	79.3 ± 8.04	64.5 ± 4.82
Side Tested		
Dominant	8	5
Non-Dominant	5	10

Note. BMI, Body Mass Index

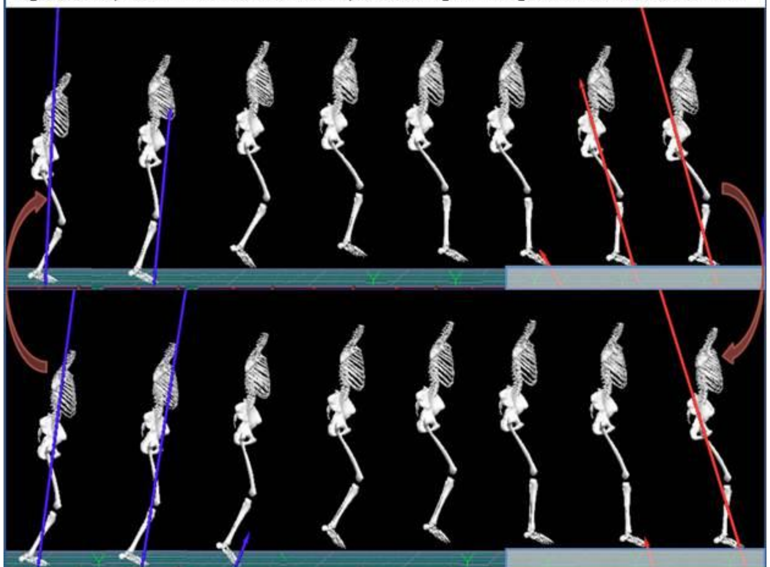
Testing Protocol

In a single session, participants completed a randomized repeated measures testing protocol. Testing included, in order: measurement of height and weight; a warm-up consisting of a 5 minute treadmill walk at 3.5 mph followed by dynamic preparatory exercises (high-knee running, heel-to-gluteals running, lateral shuffles, carioca running, heel walking, and toe walking); placement of reflective markers; standing kinematic data calibration; and motion analysis assessment of a single leg box hops task at four levels of BWS (0%, 10%, 20%, and 30%) in random order determined prior to testing. A single limb was tested (dominant or non-dominant), also randomly determined prior to testing (**TABLE 1**). Limb dominance was determined by asking which leg would be used to kick a ball for distance.

Box Hop Task

Despite their strong relation to injury,[17,18] studies exploring single leg plyometric hop tasks are particularly rare. Bobbert and Richard Casius[26] attempted to examine repetitive hopping at four height levels (maximal, 75% maximal height, 50% maximal height, and 25% maximum height) but had difficulty in both ensuring consistency within maximal and submaximal levels and in defining those levels. Their hop conditions were eventually defined as maximal, high intermediate (lower than maximal on average), low intermediate (lower than high intermediate on average), and low (lower than low intermediate on average). In our preliminary testing, maximal hop height tended to increase with BWS, confounding our kinetic results with the effects of momentum. We therefore chose a box hops task in order to create consistency in jump height between repetitions and BWS levels, as well as between subjects. The single leg hopping task consisted of two separate counter-movements (**FIGURE 2**). Subjects gained their balance in single leg stance, hopped up onto a 13 cm box that was 400 mm by 600 mm in area, and then immediately reversed to hop back down. The task of hopping on and off the box was repeated 10 times continuously without pause. The counter-movement on the lower surface (landing from the box and immediately hopping back up) involved greater force absorption and power development, and was the focus of our analysis. The task was described verbally and demonstrated prior to initial testing. Subjects were cued to avoid pausing between hops and to land with their foot fully on the box, rather than on the edge, to maintain task consistency between BWS levels. Prior to collecting data for analysis at each level of BWS, participants practiced until they verbally confirmed they were comfortable with performing the task at each level of BWS.

Figure 2 Stop-action illustration of box hops task using still images from the Visual3D model

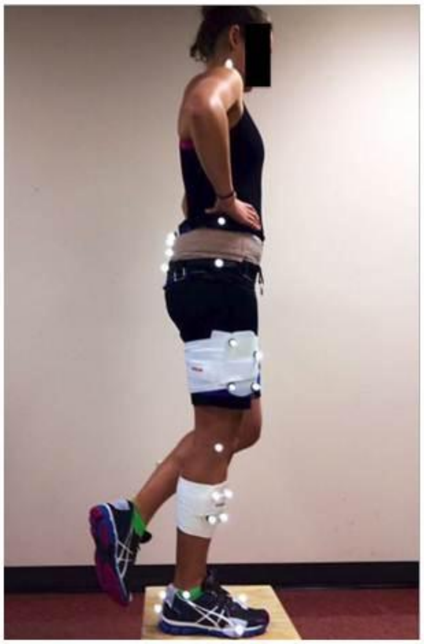


Sequence of movement progresses clockwise, with the hop up to the box on the top and the hop down off the box on the bottom. The countermovement used for analysis exists in the instant between hopping down and hopping up, illustrated here as the arrow on the left.

Motion Analysis

Kinematic and kinetic analysis of the box hops task was performed using a VICON Nexus motion capture system with 8 MXF40 cameras (Oxford Metrics, Ltd., London, UK) and a 400x600 mm force plate (AMTI, Watertown, MA) capturing tri-planar ground reaction forces. Video data were sampled at 200 Hz; force plate data were sampled at 1200 Hz. Each countermovement from the box to the ground and back up was analyzed separately with the first and last hops excluded, resulting in 8 repetitions per BWS level averaged together for analysis.

Figure 3 Retroreflective marker array for motion analysis



Joint markers at iliac crests, greater trochanter, femoral condyles, and malleoli were removed following standing calibration. Thigh and shank shells and joint markers of femoral condyles and malleoli were only applied to the tested limb.

Retro-reflective markers (14 mm diameter) were placed as in **FIGURE 3** and per previous work[12,27] to identify the joint centers of the ankle, knee, and hip of the tested limb, as well as to define the pelvis. Rigid, thermoplastic shells with 4 markers affixed to their surfaces were attached to the shank and thigh of the tested limb using elastic wraps (SuperWrap TM, Fabrifoam, Inc. Exton, PA), which allowed tracking of the three-dimensional position of each segment. A shell was also affixed over the sacrum to track the pelvis. Four markers placed on the superior and inferior heel counter of the shoe and the 1st and 5th metatarsal heads tracked foot movement. A standing calibration was performed prior to completing the landing trials to identify joint centers with respect to each segments coordinate system. Joint center anatomical markers were then removed, with the shells and remaining markers indicating position of the aforementioned segments throughout testing.

Marker trajectories and force plate data were respectively low pass filtered at 12 and 50 Hz with 4^{th} order phase-corrected Butterworth filters. The vertical ground reaction forces (VGRF) and internal joint moments were normalized to each individual's body weight (BW), and the loading rate for each trial was expressed as peak VGRF divided by the time from initial contact to peak knee flexion. Joint kinematics were calculated using Euler angles, and joint kinetics were calculated with inverse dynamics using rigid body analysis through custom applications with Visual 3D software (Visual3D, Version 4.75.29, C-motion Inc., Rockville, MD).

Data Analysis

Peak joint angles and moments between initial contact on the force place to take-off were averaged between the 8 repetitions and within levels of BWS for each subject. A total support moment was generated by summing the peak moments of the hip, knee, and ankle. The relative contribution of each joint was assessed through the ratio of the individual joint moment to the total support moment (percentage support moment). Descriptive statistics (mean, SD) were developed for all variables of interest, including BWS load variability. A repeated-measure ANOVA between BWS level and each dependent variable of peak hip, knee, and ankle flexion; peak hip, knee, and ankle moment; peak VGRF; and loading rate were performed to screen for differences in means. If the ANOVA achieved significance by BWS Level, then post-hoc pairwise comparisons between BWS levels were performed via single tailed *t*-tests with a Bonferroni adjustment. All statistical analyses were performed with SPSS Statistics 20.0 (IBM Corp, Armonk, NY) with an alpha level set to P=.05.

RESULTS

Consistency of Unloading Force

At 10% BWS, the vertical force varied by a mean 19% (SD=5%) of the target force. At 20% BWS, the variation in force averaged 10% (SD=3%), and at 30%, the variation was 7% (SD=4%) of the target force. For example, in a representative subject with a target 20% BWS of 16.7 kg, the vertical load at the top of the jump was 15.9 kg, and the load at the bottom of the jump was 17.5 kg.

Kinematics and kinetics at 0% BWS

Table 2 Peak flexion angle and external flexion moments of the hip, knee, and ankle during countermovement hop at increasing levels of BWS, mean (SD)

	Hip				Knee				Ankle			
BWS Level	Angle (°)	*P*	Moment (BW)	*P*	Angle (°)	*P*	Moment (BW)	*P*	Angle (°)	*P*	Moment (BW)	*P*
0%	21.4 (7.8)		1.8 (0.4)		44.6 (5.5)		2.7 (0.5)		25.0 (3.4)		2.9 (0.6)	
10%	20.1 (7.3)	*0.03*	1.5 (0.4)	*0.00*	45.4 (6.5)	0.45	2.6 (0.4)	*0.00*	24.1 (3.7)	*0.00*	2.9 (0.5)	0.18
20%	19.6 (5.9)	0.22	1.4 (0.3)	*0.01*	45.4 (7.4)	0.23	2.4 (0.4)	*0.00*	24.0 (4.1)	0.39	2.7 (0.5)	*0.00*
30%	20.4 (7.2)	*0.04*	1.3 (0.4)	*0.02*	48.2 (8.3)	*0.00*	2.2 (0.4)	*0.01*	24.7 (4.2)	*0.05*	2.4 (0.6)	*0.00*

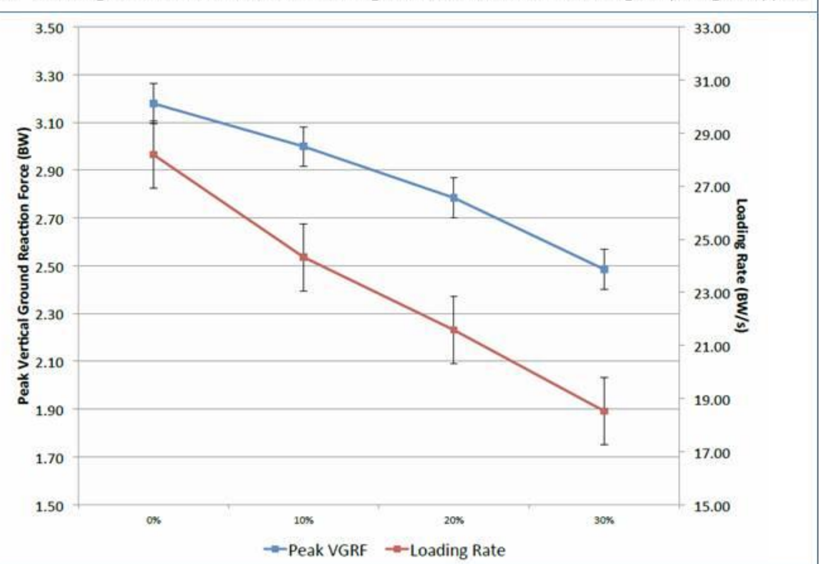
Note. BW, body weights; BWS, body weight support. *P*-values are reported for changes between adjacent BWS levels (eg, 0% - 10%, 10% - 20%).

Peak VGRF during the countermovement averaged 3.2 BW (SD=0.5), with an average peak loading rate of 28.2 BW/s (SD=8.3). Peak sagittal plane angles and moments at the hip, knee, and ankle are reported in **TABLE 2**. The hip contributed 24% (SD=5%), the knee 37% (SD=5%), and the ankle 39% (SD=5%) to the total sagittal support moment.

Effects of Progressive BWS on Kinetics

From their respective initial peaks at 0% BWS described above, the peak VGRF and peak loading rate decreased significantly (*P*<0.001) with each increase in BWS (**FIGURE 4**). Individual joint moments at each BWS level are reported in **TABLE 2**. There was a statistically significant decrease in both hip and knee moment with each increase of BWS, as well (*P*<0.001). The average hip moment decreased by 0.25 BW from 0% to 10% BWS, 0.11 BW from 10% to 20% BWS, and an additional decrease of 0.11 BW from 20% to 30% BWS. The

Figure 4 Vertical ground reaction forces and loading rates decrease with increasing body weight support



Note. VGRF, vertical ground reaction force. BW, body weights. Vertical ground reaction forces and loading rates are normalized to body weight. Error bars are reported as standard error of the mean.

knee moment decreased by 0.16 BW, 0.23 BW, and 0.15 BW, respectively with each 10% addition of BWS. There was no significant decrease in the ankle moment from 0% to 10% BWS (*P*=0.18), though there was a significant decrease of 0.21 BW between 10% and 20%, and another of 0.29 BW from 20% to 30% (*P*<0.001). However, there was no statistically or clinically significant change in percent support moment at any joint with increasing BWS. At 10% and 20% BWS respectively the hip contributed 22% (SD=5%) the knee contributed 37% (SD=5%) and 37% (SD=6%) and the ankle contributed 41% (SD=5%) and 41% (SD=5%). At 30% BWS, the hip contributed 22% (SD=5%), the knee 38% (SD=6%), and the ankle 40% (SD=8%) to the total support moment.

Effects of progressive BWS on kinematics

There was a statistically significant decrease in peak ankle dorsiflexion from 0% to10% BWS (0.91°; *P*=0.002) and an increase from 20% to 30% BWS (0.3°; *P*=0.05), but no change in dorsiflexion between 0% and 30% BWS. Similarly, there was a statistically significant decrease in hip flexion from 0% to 10% BWS (1.3°; *P*=0.02) and an increase from 20% to 30% BWS (0.9°; *P*=.04), but no change in hip flexion from 0% to 30% BWS. Knee flexion, however, increased by 2.8° (*P*<0.001) between 20% and 30% BWS, for a total increase of 3.6° from 0% to 30% BWS (*P*<0.001).

DISCUSSION

Our first step was to describe the biomechanical characteristics of a repetitive single leg countermovement task, or hop. A sagittal plane hurdle hop has been described in the context of plyometric training programs,[28,29] but relatively little information is available on the kinematic and kinetic behaviors that compose repetitive single leg hops in the sagittal plane. Utilizing a box hop, rather than a maximal or sub-maximal hop,[26] allowed task consistency between subjects and between BWS trials. In our sample, the box hops task is primarily an ankle-dominant movement in terms of torque demand, with the ankle representing approximately 40% of the total support moment regardless of BWS status. The hip, knee, and ankle all displayed markedly decreased peak flexion angles and increased loading rates compared with previously described dual-stance plyometric tasks, such as a drop vertical jump (DVJ) or countermovement jump. For instance, Malfait et al.[30] found a mean of 96° knee flexion and 75° hip flexion during a 0.3 meter DVJ. Further, Zhang et al.[31] demonstrated a shift in landing strategy toward one dominated by the ankle, rather than the hip or knee, as landing stiffness increased. Our data are also consistent with those of Wang,[32] who found decreased hip and knee flexion in a single leg versus double-leg countermovement task.

The application of BWS effectively mitigates impact loading during a box hop task, though not via a 1:1 relationship. Increasing the level of BWS to 30% resulted in an average 22.5% decrease in peak VGRF. Additionally, there appears to be a differential adaptation in sagittal joint moment to BWS. The peak hip moment decreases with the addition of 10% BWS then changes very little with added support. The peak knee moment decreases somewhat less at this level, with a greater decrease at 20% BWS, and similarly to the hip changes very little at 30% BWS. In contrast, the ankle moment is less responsive to lower levels of BWS, changing more at 20% and 30% BWS. The plantar flexors may be preferentially affected at high speeds. Lewek[33] found a significant interaction between gait speed and BWS in decreasing ankle moment and propulsive power, with a greater effect of BWS with increasing gait speed, though neither the knee nor hip moments were concurrently examined.

The potential for BWS as an adjunct to training in plyometric or other tasks with relatively large excursions of the center of mass is high. The minimal kinematic change and a similar relative apportionment of load across the kinetic chain, regardless of BWS level, indicate maintenance of task specificity. The presumed high total loads inherent to plyometric activity prevent high repetition and limit training with patient populations to end-stage rehabilitation.[14] Healthy athletic populations limit plyometric activity as well. Indeed, the box hops task generated an average peak VGRF of 3.2 body weights. In comparison, Kluitenberg[34] recently reported an average VGRF of 2.5 BW in slow running and 2.7 BW in fast running Increasing BWS to 20% decreased average loading of the box hops task to within this range.

We did not examine the neuromuscular behaviors underlying the box hops task via electromyography, nor their response to BWS. Preferential changes in recruitment may well be present, given the changes in external moment. However, neither Franz et al.[35] nor Lewek[33] found significant changes in plantarflexor recruitment with increasing BWS during a walking task, contrary to expectations. While the kinematics and kinetics of the ankle joint certainly change, the passive elements of the plantar flexor musculature may play such a large role in energy return that the effect of BWS on contractile tissue is negligible. Indeed, such a schema is described as a key difference between walking and running gaits, with walking gaits deriving most of their efficiency from the pendular conservation of mechanical energy between potential and kinetic states.[36] Running gaits, in contrast, rely on elastic elements to store and return mechanical energy, and as such do not conform to many theoretical models of walking.[22] The different mechanisms of energy storage and return also create different responses to BWS. Walking with BWS frequently increases metabolic demand due to a disruption of the mechanical energy exchanges,[37] while running with BWS necessitates increased speed to maintain metabolic demand.[38] As repetitive hopping conforms more to the elastic construct of energetic exchange, we may expect similar responses to BWS between repetitive hopping and running with regard to muscle recruitment and demand.

The current study was focused on examining the response of healthy subjects, rather than that of subjects with injury, and there may be a differential effect of BWS on the kinematics and kinetics of plyometric tasks within an injured population. However, the description of a replicable, repetitive plyometric task and validation of BWS was deemed of greater importance at this time. Given the difficulty the healthy, athletic participants had completing the task at 0% BWS, we felt that injured participants would have provided an incomplete comparison.

In summary, the box hops task typically involves decreased hip and knee excursion from that seen in double-leg countermovement tasks, as well as increased joint torques and VGRF as expected. The addition of BWS at dose at or below 30% of body weight had little to no effect on the kinematics of the lower extremity. While BWS did decrease joint moments, the relative support moment of each joint was preserved across BWS levels. BWS may therefore mitigate joint loads to safe levels for high repetition training while maintaining the kinematic and relative kinetic specificity of a plyometric or countermovement task.

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REFERENCES

1. Mehrholz J, Pohl M, Elsner B. Treadmill training and body weight support for walking after stroke. *The Cochrane database of systematic reviews.* 2014;1:CD002840.
2. Combs SA, Dugan EL, Ozimek EN, Curtis AB. Bilateral coordination and gait symmetry after body-weight supported treadmill training for persons with chronic stroke. *Clin Biomech (Bristol, Avon).* 2013;28(4):448-453.
3. Morawietz C, Moffat F. Effects of locomotor training after incomplete spinal cord injury: a systematic review. *Archives of physical medicine and rehabilitation.* 2013;94(11):2297-2308.
4. Wessels M, Lucas C, Eriks I, de Groot S. Body weight-supported gait training for restoration of walking in people with an incomplete spinal cord injury: a systematic review. *J Rehabil Med.* 2010;42(6):513-519.
5. Moore MN, Vandenakker-Albanese C, Hoffman MD. Use of partial body-weight support for aggressive return to running after lumbar disk herniation: a case report. *Archives of physical medicine and rehabilitation.* 2010;91(5):803-805.
6. Saxena A, Granot A. Use of an anti-gravity treadmill in the rehabilitation of the operated achilles tendon: a pilot study. *The Journal of foot and ankle surgery : official publication of the American College of Foot and Ankle Surgeons.* 2011;50(5):558-561.
7. Takacs J, Leiter JR, Peeler JD. Novel application of lower body positive-pressure in the rehabilitation of an individual with multiple lower extremity fractures. *J Rehabil Med.* 2011;43(7):653-656.
8. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
9. Chmielewski TL, Trumble TN, Joseph AM, et al. Urinary CTX-II concentrations are elevated and associated with knee pain and function in subjects with ACL reconstruction. *Osteoarthritis Cartilage.* 2012;20(11):1294-1301.
10. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *Am J Sports Med.* 2010;38(11):2201-2210.

11. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
12. Elias ARC, Mizner RL, Hammill CD. Adaptation of Quadriceps and Hamstring Co-contraction Following Landing Instruction in Patients with ACL Reconstruction. *J Orthop Sports Phys Ther.* 2014;IN PRESS.
13. Wilmink RJ, Nichols TR. Distribution of heterogenic reflexes among the quadriceps and triceps surae muscles of the cat hind limb. *Journal of neurophysiology.* 2003;90(4):2310-2324.
14. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *J Orthop Sports Phys Ther.* 2006;36(5):308-319.
15. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.
16. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
17. Boden BP, Dean GS, Feagin JA, Jr., Garrett WE, Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics.* 2000;23(6):573-578.
18. Olsen OE, Myklebust G, Engebretsen L, Bahr R. Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *The American journal of sports medicine.* 2004;32(4):1002-1012.
19. Sugisaki N, Okada J, Kanehisa H. Intensity-level assessment of lower body plyometric exercises based on mechanical output of lower limb joints. *Journal of sports sciences.* 2013;31(8):894-906.
20. Kerr AL, Cheng SY, Jones TA. Experience-dependent neural plasticity in the adult damaged brain. *Journal of communication disorders.* 2011;44(5):538-548.
21. Threlkeld AJ, Cooper LD, Monger BP, Craven AN, Haupt HG. Temporospatial and kinematic gait alterations during treadmill walking with body weight suspension. *Gait & posture.* 2003;17(3):235-245.
22. Donelan JM, Kram R. Exploring dynamic similarity in human running using simulated reduced gravity. *J Exp Biol.* 2000;203(Pt 16):2405-2415.
23. Ackermann M, van den Bogert AJ. Predictive simulation of gait at low gravity reveals skipping as the preferred locomotion strategy. *Journal of biomechanics.* 2012;45(7):1293-1298.
24. Briggs KK, Lysholm J, Tegner Y, Rodkey WG, Kocher MS, Steadman JR. The reliability, validity, and responsiveness of the Lysholm score and Tegner activity scale for anterior cruciate ligament injuries of the knee: 25 years later. *The American journal of sports medicine.* 2009;37(5):890-897.
25. Briggs KK, Steadman JR, Hay CJ, Hines SL. Lysholm score and Tegner activity level in individuals with normal knees. *The American journal of sports medicine.* 2009;37(5):898-901.

26. Bobbert MF, Richard Casius LJ. Spring-like leg behaviour, musculoskeletal mechanics and control in maximum and submaximum height human hopping. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences.* 2011;366(1570):1516-1529.
27. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
28. Arabatzi F, Kellis E, Saez-Saez De Villarreal E. Vertical jump biomechanics after plyometric, weight lifting, and combined (weight lifting + plyometric) training. *J Strength Cond Res.* 2010;24(9):2440-2448.
29. Struminger AH, Lewek MD, Goto S, Hibberd E, Blackburn JT. Comparison of gluteal and hamstring activation during five commonly used plyometric exercises. *Clinical biomechanics.* 2013;28(7):783-789.
30. Malfait B, Sankey S, Firhad Raja Azidin RM, et al. How reliable are lower-limb kinematics and kinetics during a drop vertical jump? *Medicine and science in sports and exercise.* 2014;46(4):678-685.
31. Zhang SN, Bates BT, Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc.* 2000;32(4):812-819.
32. Wang LI. The lower extremity biomechanics of single- and double-leg stop-jump tasks. *Journal of sports science & medicine.* 2011;10(1):151-156.
33. Lewek MD. The influence of body weight support on ankle mechanics during treadmill walking. *J Biomech.* 2011;44(1):128-133.
34. Kluitenberg B, Bredeweg SW, Zijlstra S, Zijlstra W, Buist I. Comparison of vertical ground reaction forces during overground and treadmill running. A validation study. *BMC musculoskeletal disorders.* 2012;13:235.
35. Franz JR, Glauser M, Riley PO, et al. Physiological modulation of gait variables by an active partial body weight support system. *J Biomech.* 2007;40(14):3244-3250.
36. Cavagna GA, Saibene FP, Santi GF, Margaria R. Analysis of the Mechanics of Locomotion. *Experimental medicine and surgery.* 1963;21:117-126.
37. Griffin TM, Tolani NA, Kram R. Walking in simulated reduced gravity: mechanical energy fluctuations and exchange. *Journal of applied physiology.* 1999;86(1):383-390.
38. Grabowski AM, Kram R. Effects of velocity and weight support on ground reaction forces and metabolic power during running. *J Appl Biomech.* 2008;24(3):288-297.

HIGH REPETITION JUMP TRAINING COUPLED WITH BODY WEIGHT SUPPORT IN A PATIENT WITH ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION:

A CASE REPORT

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Disclosures: the University of Montana has submitted a patent associated with the intellectual property of the body weight support system described in this manuscript.

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Background and Purpose: Patients frequently experience long-term deficits in functional activity following anterior cruciate ligament reconstruction, and commonly present with decreased confidence and poor weight acceptance in the surgical knee. Adaptation of neuromuscular behaviors may be possible through plyometric training. Body weight support decreases intensity of landing sufficiently to allow increased training repetition. The purpose of this case report is to report the outcomes of a patient with anterior cruciate ligament reconstruction treated with high repetition jump training coupled with body weight support (BWS) as a primary intervention strategy.

Case Description: A 23-year old female who had right anterior cruciate ligament reconstruction seven years prior presented with anterior knee pain and effusion following initiation of a running program. Following visual assessment of poor mechanics in single leg closed chain activities, landing mechanics were assessed using 3-D motion analysis of single leg landing off a 20 cm box. She then participated in an eight-week plyometric training program using a custom body weight support system. The International Knee Documentation Committee Subjective Knee Form (IKDC) and the ACL-Return to Sport Index were administered at the start and end of treatment as well as at follow-up testing.

Outcomes: The subject's IKDC and ACL-Return to Sport Index scores increased from 68% and 43% to 90% and 84% respectively with training and were retained over time. Knee and hip flexion angles increased from 47° and 53° to 72° and 80° respectively. Vertical ground reaction forces in landing decreased with training from 3.8 N/kg to 3.2 N/kg. All changes were retained two months following completion of training.

Discussion: The subject experienced meaningful changes in overall function. Retention of mechanical changes suggests that her new landing strategy had become a habitual pattern. Success with high volume plyometric training is possible when using BWS. Clinical investigation into the efficacy of body weight support as a training mechanism is needed.

Level of Evidence: Level 4

Key Words: plyometrics, biomechanics, training volume

BACKGROUND AND PURPOSE

More than 200,000 people injure the anterior cruciate ligament (ACL) of their knee annually in the United States. Of these, approximately 65% undergo surgical ACL reconstruction.[1] Initial outcomes following ACL reconstruction are quite good, with resolution of knee laxity and return to independent activities of daily living within three months.[2-4]

Although current post-operative protocols allow return to normal athletic activity within six months of surgery, a preponderance of recent evidence has shown that many patients have functional outcomes that are poorer than expected in the years following surgery.[5-11] Patients who have undergone ACL reconstruction often experience chronic impairment in mechanical performance of the operated limb.[12] Specifically, deficits in eccentric knee flexion have been demonstrated during the weight acceptance phase of gait as well as in higher intensity tasks such as stair descent and jump landing.[13-16] Decreased knee flexion during weight acceptance may also contribute to a decreased ability to absorb ground reaction forces, leading to higher vertical ground reaction forces (VGRF) when compared to the uninjured side and healthy controls.[15,16] Additionally, people with ACL reconstruction frequently demonstrate high levels of fear of movement, or a lack of confidence in the knee.[5,17,18]

Ardern et al[18] and Chmielewski[17] have both demonstrated that psychological impairments such as fear of movement and lack of confidence correlate with poor return to activity outcomes. Recent data[19] have demonstrated a negative correlation between psychological impairments and absorption of vertical forces in the surgical knee. Specifically, increased fear of movement correlates with decreased ability to absorb vertical forces. Together, mechanical and psychological impairments have been associated with a 63% rate of return to pre-injury levels of physical activity, a 14% to 25% re-injury rate, and a 50% risk of early-onset osteoarthritis.[5,20-23] Despite the high prevalence of difficulty returning to full function, there has been relatively little research performed exploring interventions designed to address chronic post-surgical psychological and mechanical impairments.

Plyometric or jump training has been recommended to improve mechanical deficits seen in the lower extremity following ACL reconstruction.[4,24] However, the evidence supporting this recommendation has primarily been from the literature on primary injury prevention in healthy athletes,[25-33] and as such the specifics of exercise dosage may not translate to an injured population. Chmielewski[34] reviewed considerations for dosing plyometric exercise following injury, and recommended low repetition due to high ground reaction forces and rapid loading rates. In two recently published clinical commentaries describing optimal post-ACL reconstruction rehabilitation, plyometric training is advised when specific strength and functional criteria are met (generally after 12 weeks), but no specific repetition recommendations are made.[4,24] Recommendations for healthy athletes range from 20 contacts per session to 120 contacts per session.[26,30,35,36] The inherently high intensity of plyometric activity may cause clinicians to further reduce repetition during training, so as to avoid further injury to an already at-risk knee joint.[23,34] Unfortunately, given the complexity and potential chronicity of the mechanical deficits involved post-surgically, low repetition training may not provide sufficient neuromuscular stimulus to allow modification of habitual movement patterns.[37] While the literature regarding ways to optimize motor learning can be contradictory, it does seem that higher training volumes in the form of increased repetition of a task improves retention of that skill.[38]

High levels of fear and low confidence common after ACL reconstruction may also unduly influence a patient's ability to complete effective plyometric training. The phenomenon of fear avoidance in chronic pain literature[39] bears a marked resemblance to the phenomenon of psychological impairment limiting physical activity following ACL reconstruction. Given this similarity, effective treatment of psychological impairment following surgery may follow the treatment paradigm most successfully associated with fear avoidance. [40,41] Kinesiophobia in athletes following ACL reconstruction may therefore be effectively treated through graded exposure to the fear-inducing stimulus. In the case of plyometric training, landing from a jump may be considered a fear-inducing stimulus. However, as Chmielewski[34] states, landing on a single leg is inherently high intensity, and there are very few mechanisms by which the intensity of the landing task can be reduced while maintaining specificity of motion.

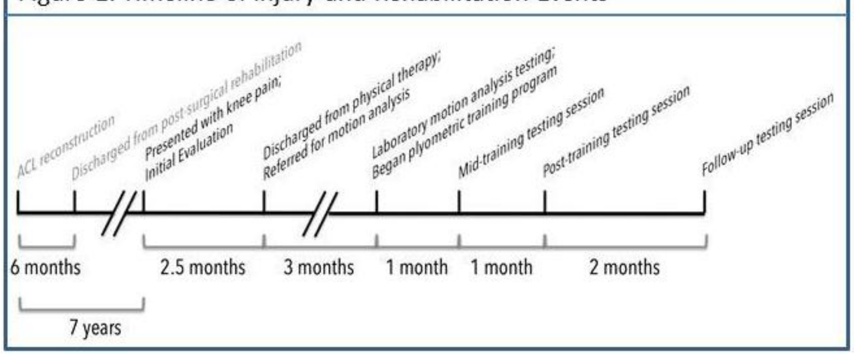
One method of reducing landing intensity is via body weight support (BWS), which may decrease intensity enough to allow higher repetition plyometric training than normally recommended and to accurately grade exposure to landing tasks. Forms of BWS have been used extensively in rehabilitation of neurological injury[42,43] and for orthopaedic rehabilitation[44-46] as well. Unfortunately, aquatic training, plyometric leg press, and treadmill-bound systems do not allow for specificity of movement or sport-specific training. The natural hydraulics of the aquatic environment can result in abnormal shear forces through the joints.[47] A plyometric leg press requires activation of the hip flexors to maintain the feet in the line of fall, and only allows for sagittal plane movement, without the ability to move freely in three-dimensional space. A treadmill-bound system works by raising the center of mass, disallowing relatively large vertical excursions such as those seen in a jump or hop. To date, BWS systems primarily support walking and running tasks, as the vertical speed of jumping is generally too high for even motorized BWS systems to maintain constant levels of BWS. However, for this study, a novel BWS system was developed to allow specificity of movement during tasks involving vertical excursion, as well as sport specific training including cutting and pivoting motions. Appropriate utilization of this novel BWS system during plyometric training may improve mechanical and psychological, and thereby functional, outcomes following ACL reconstruction.

The purpose of this case report is to report the outcomes of a subject with a previous history of ACL reconstruction treated with high repetition jump training coupled with BWS as a primary intervention strategy. The changes in landing mechanics, psychological readiness for activity, and functional outcomes are detailed.

CASE DESCRIPTION

Patient History and Systems Review

Figure 1. Timeline of Injury and Rehabilitation Events



The subject was a 23 year-old female (BMI: 22.5) who presented with right anterior knee pain of gradual onset following initiation of a running program for fitness eight months previously. At the time of her initial evaluation (**FIGURE 1**), the subject was unable to run >1 mile due to pain rated at 5/10 on a visual analog scale. Additionally, she had discontinued playing intramural basketball due to pain. She was able to participate in all activities of daily living without pain with the exception of ascending and descending stairs, and had a Lower Extremity Function Scale (LEFS) score of 71/80. The subject had an unremarkable past medical history with the exception of a right ACL reconstruction with hamstring autograft seven years previously (**FIGURE 1**). Her history was otherwise negative for other lower extremity injuries or conditions. A systems review was unremarkable, and the subject otherwise healthy. The subject reported that magnetic resonance imaging two months prior to evaluation demonstrated a “bone bruise” to the tibial plateau, but further detail was unavailable. Her goals were to progress to running at least three miles without pain, and to play intramural basketball without concern for her knee. The subject was initially examined and treated by a licensed physical therapist and Fellow of the American Academy of Orthopaedic Manual Physical Therapists.

Examination

Passive range of motion (PROM) was limited to 137 degrees of flexion and 0 degrees of hyperextension, compared to 147 degrees of flexion and 5 degrees of hyperextension on the left. She also reported deep joint pain at end range in both directions. Tibiofemoral joint mobility testing revealed normal end-feel and mobility with anterior/posterior glides and distraction, but decreased pain with distraction. Her knee flexion strength was rated at a 4+/5 as compared to 5/5 on the left; knee extension strength in manual muscle testing was symmetrical side to side for a grade of 5/5.[48] However, she was unable to perform a single leg squat on the right without femoral adduction and internal rotation, and the depth of her single leg squat was limited compared to the left side. Single leg stance on the right was notable for excessive use of a hip strategy to maintain balance compared to the left. Excessive lumbar extension and poor control of hip adduction were observed during walking and running gait, resulting in excessive pelvic drop during the stance phase of both gaits.

The subject was diagnosed with internal derangement of the knee with effusion, decreased PROM, and decreased functional capacity. She also displayed dysfunctional biomechanics in closed kinetic chain activities. Due to her work and school schedule, she underwent six sessions of physical therapy over a 10-week period (Figure 1). Treatment consisted of manual therapy for joint and soft tissue mobility to increase PROM and decrease effusion, single leg squats on a Total Gym® (Total Gym Global Corp., San Diego, CA) with cueing for knee, hip, and lumbar control, and running gait training on a treadmill to reduce pelvic drop during stance and lessen frontal plane valgus knee alignment.

Clinical Impression 1

After 10 weeks of physical therapy as described above, the subject's PROM and gross strength deficits by manual muscle testing were equal to the contralateral side. She was progressing in a walk/jog program without pain, with a LEFS score of 77/80 at the end of the 10-week period. However, her dysfunctional movement patterns in closed kinetic chain activities persisted. Her continued inability to single leg squat on the surgical side led her physical therapist to refer the subject for biomechanical testing in the University of Montana Movement Science Laboratory (**FIGURE 1**). Due to academic scheduling constraints, the subject was unable to complete laboratory testing for another three months (**FIGURE 1**). At the time of laboratory testing (**FIGURE 1**) as described below, she reported she had been unable to progress in running without pain, and continued to experience effusion after running >one mile. Her history, inclusive of the initial evaluation and treatment described above and considering her history of a non-contact ACL injury, indicated a persistent problem in movement coordination in closed-chain tasks, particularly those involving a single leg and/or impact. The subject was informed that data concerning her evaluation and treatment would be submitted for a case report, and she consented to submission.

Examination

The full laboratory examination consisted of, in order, administration of the International Knee Documentation Committee Subjective Knee Form (IKDC) and the ACL-Return to Sport Index (ACL-RSI); height and body mass measurement with a standard physician's scale; a five-minute treadmill walking warm-up; PROM measurement and effusion grading; knee flexion and extension strength testing with force dynamometry; application of retroreflective markers; and biomechanical analysis of a single leg landing from a 20 cm box as previously described.[49,50] Testing and further intervention described below were performed by a licensed physical therapist with board certification as an orthopaedic specialist and certification for plyometric training for ACL prevention through SportsMetrics ™.

Outcome Measures and Clinical Tests

The IKDC was administered as a validated measure of patient-reported function for athletes, which avoids ceiling effects seen in other functional outcome measures, including the LEFS.[51,52] The ACL-RSI, a validated tool which measures confidence on a 0-100 scale, was administered to provide a measure of psychological readiness for return to activity.[53,54] Effusion was tested using the stroke test.[55] Passive ROM was measured with a standard long arm goniometer as previously described.[56]

MVIC Testing

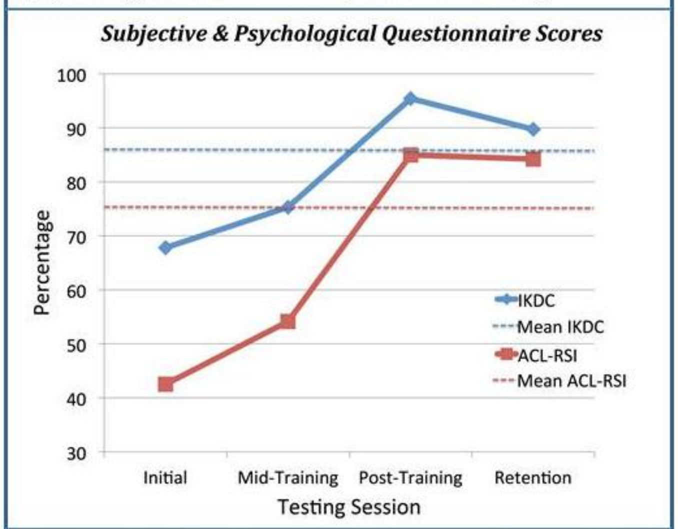
Knee flexor and extensor isometric strength was tested in sitting using a Kin-Com 125AP dynamometer (Chattanooga Group, Inc., Chattanooga, TN) utilizing previously published methods.[49,57] The more precise measure of strength afforded by dynamometry was considered important given the relatively poor sensitivity of manual muscle testing to side-to-side differences.[58] The knee was strapped into 60 degrees of flexion for flexor testing and 90 degrees of flexion for extensor testing. The uninvolved limb was tested first to provide the subject with a target force as well as to develop task familiarity. Visual and verbal encouragement were provided during trials. At least 1 minute of rest was allowed between trials. When force production decreased or failed to increase more than 5% from the previous trial, the testing was complete and the trial with the highest force production was utilized for analysis. Force data were sampled at 200 Hz utilizing a BIOPAC MP 150 (BIOPAC Systems, Inc., Santa Barbara, CA) data acquisition workstation with Acqknowledge v.3.7 software and processed with a 6 Hz low pass filter prior to determining maximal force production.

Biomechanical Analysis of Single Leg Landing

A single leg landing from a 20 cm box as previously described[49,57] was chosen for testing, as the primary mechanism of continued pain for the subject was running, which consists of multiple single leg landings. Her difficulty with maintaining desired dynamic postures during closed kinetic chain single leg squat activities also played into this decision. Further, her history of non-contact ACL injury suggested potential neuromuscular faults,[27,59] and the most frequent mechanism of non-contact ACL injury is a single leg landing.[50] The subject stood approximately 10 cm from the edge of a 20 cm high box, hands on hips, and was instructed to gain her balance on a single leg before hopping off the box onto a force plate with her eyes looking forward. She performed five successful test trials of the single-leg landing task after five practice trials on each leg. A trial was deemed successful if she maintained a single leg stance for at least 2 seconds upon landing, and regained dual leg stance in a controlled manner.

Kinematic data were obtained during the single-leg landing task using an eight-camera VICON Nexus system at 200 Hz (Oxford Metrics, Ltd., London, UK). Retro-reflective markers (14 mm diameter) were placed in a Cleveland Clinic model per previously published methods[49,57] to allow tracking of the three-dimensional position of bilateral feet, shanks, thighs, pelvis, and trunk. A standing calibration was performed prior to completing the landing trial to identify joint centers with respect to each segment's coordinate system.

Figure 2. Change in patient-reported function and psychological readiness for sport with training.



*IKDC, International Knee Documentation Committee Subjective Knee Form. Mean value for 18-24 year old females, from Anderson et al (2006).
†ACL-RSI, Anterior Cruciate Ligament-Return to Sport Index. Mean value for athletes who have returned to sport, from Muller (2014).
‡ Mid-training testing occurred at week 4 of training. Post-training testing occurred after full 8 week training period. Retention testing occurred after 8 weeks without training or contact with the investigators.

A 400 x 600 mm force plate (AMTI, Watertown, MA) interfaced with the VICON Nexus system captured ground reaction forces during landing. Force plate data were sampled at 1200 Hz. Marker trajectories and force plate data were filtered at 12 and 50 Hz respectively with fourth-order phase-corrected Butterworth filters. The peak vertical ground reaction forces (VGRF) and joint moments were normalized to the subject's body mass. Joint kinematics were calculated using Euler angles, and joint kinetics were calculated with inverse dynamics using rigid body analysis through custom applications with Visual 3D software (Visual3D, Version 4.75.29, C-motion Inc., Rockville, MD). Joint angles and moments were time normalized to 100 increments from initial contact on the force plate to peak knee flexion during landing to allow calculation of an ensemble average across trials, as the time between those events varied slightly between trials.

Clinical Impression 2

Patient-reported outcome measures obtained during the laboratory testing showed moderate to severe decreases in self-reported function and confidence (**FIGURE 2**), with an initial IKDC score of 67.8% and an ACL-RSI score of 42.5%. Anderson et al[60] reported an average IKDC score for people with a history of any right knee surgery (median of five to 10 years prior) of 56.3%. The mean score for 18-24 year old women inclusive of those with and without knee injury was reported as 86%. The subject's IKDC score put her in the 15th percentile of 18-24 year old women with or without injury.[60] Initial validation of the ACL-RSI scale showed a mean ACL-RSI score of 39.1% for athletes who have given up sport following ACL reconstruction. Athletes who planned to return but had not yet done so scored a mean of 54.9%.[53] Further, an ACL-RSI score of 52.3% has been found to be a cut-off point between those athletes that eventually return to sport and those that do not.[54] The subject's initial ACL-RSI score of 42.5% predicted that she would not return to sport, but had not yet

Table 1. Side-to-side thigh strength symmetry via force dynamometry

	Pre-Training	Post-Training†	Retention‡	Recommended§
Quadriceps	76.8%	86.4%	106.5%	85%
Hamstrings	73.2%	71.1%	127.1%	85%

*Symmetry is expressed as a ratio of the surgical side to the non-surgical side.
†Post-training testing was performed immediately following the 8-week training intervention.
‡Retention testing was performed eight-weeks following post-training testing.
§Recommended values are taken from Adams et al (2012).

given up sporting activities.

Her PROM was symmetrical side-to-side, with 145 degrees of knee flexion and 5 degrees of hyperextension. She presented with trace effusion. Her side-to-side strength symmetry, as a ratio of the involved to uninvolved torque production during isometric strength testing, was 76.8% for the quadriceps and 73.2% for the hamstrings (**TABLE 1**). These values are below suggested side-to-side strength ratios typically advised for return to sport after ACL injury, which range from 85% to 90%.[4]

Her kinematic and kinetic measures (**FIGURE 3**) illustrated a hard, stiff landing, with a relatively high VGRF and relatively little knee flexion and small internal knee extension moment. Mean VGRF, knee flexion, and knee extension moment during single leg landing in patients who have returned to activity after ACL reconstruction have been reported previously as approximately 3.5 Nm/kg body weight, 56°, and 2.5 Nm/kg body weight, respectively.[49]

The subject was deemed appropriate for a high repetition jump training intervention to target her chronic difficulties in absorbing load through the involved knee and her poor functional state. Augmenting the intervention with BWS allowed training even with the limiting factors of decreased strength and decreased confidence in her knee. All training was undertaken to directly address the subject's goal of returning to running and playing basketball.

Table 2. Intervention protocol performed twice weekly for eight weeks.

Treatment Component	Specific Task
Joint reaction check * **(for previous treatment)**	Knee pain rating on 1-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion
Warm-up	5 minute treadmill walking (3-3.5 mph) High knee running Heel-to-gluteal running High kick walking Hip wrap walking with heel raise Lunge walking
Jump Training	Per progression (Table 3)
Cool-down	5 minute treadmill walking (3-3.5 mph) Quadriceps stretch (30 seconds) Hamstrings stretch (30 seconds) Calf stretch (30 seconds) Hip abductor stretch (30 seconds)
Joint reaction check † **(for current treatment)**	Knee pain rating on 1-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion

* If knee pain was >2 levels higher than previous treatment, treatment was delayed and the next treatment did not progress in repetition or intensity. If muscle soreness did not relieve during warm-up and visually compromised landing technique, treatment was delayed. If the stroke test graded at or above a 2+ effusion, treatment was delayed and the next treatment did not progress in repetition or intensity.

† If knee pain increased >2 levels during treatment, the next treatment did not progress in repetition or intensity. Muscle soreness and fatigue was noted for comparison to the next pre-treatment check. If the stroke test graded >1 level above the pre-treatment grade, the next treatment did not progress in repetition or intensity.

Intervention

The subject participated in an individualized jump training program twice weekly for eight weeks. Each session took approximately one hour as detailed in **TABLE 2**. She did not participate in any other strengthening, training, or other physical therapy intervention during this period, with the exception of occasional intramural basketball games.

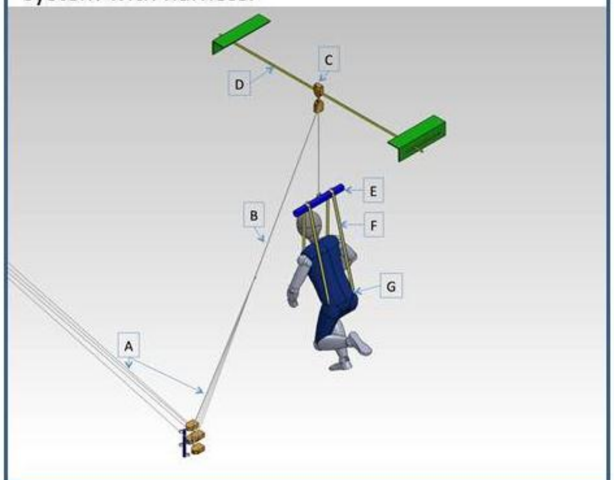
The jump training treatment progression is outlined in **TABLE 3**. Although the task progression is similar to recently published neuromuscular training protocols,[4,24,30,31] BWS allowed decreased intensity and higher repetition than the 20-120 contacts per session currently recommended for healthy athletes.[26,30,35,36] For the first six weeks, the subject performed her training in a custom BWS system designed to allow freedom of movement within a 1.5 x 3 x 4 m volume with a consistent vertical force (**FIGURES 4 & 5**), thereby providing movement and sport specificity.[61] Elastic tubing is stretched around a 75-meter pulley system and connected to a custom harness made of neoprene shorts. The final pulley is directly overhead and slides on a near-frictionless steel track bolted into the ceiling, allowing movement in any direction along a 1.5 x 3 m area on the floor. Taking advantage of the relationship between elastic recoil force and percent strain, the system is able to generate a vertical force at the center of mass that varies by less than 10% through the 3-D movement of jumping up to 1.5 m.[61] As such, the subject was able to perform high volume, sport-specific, jump landing training with decreased impact loads.[61]

Table 3. Jump training treatment progression.

Week	BWS*	Contacts by Session†		Tasks
1	30%	235	220	Vertical jumps, lateral jumps, broad jumps, spinning jumps, split jumps
2		241	270	Vertical hops, lateral hops, broad hops
3	20%	290	235	Above +
4		306	310	Triple broad hops, box hops, bounding
5	10%	275	210	Above +
6		266	305	Combination jumps, Lateral cutting
7	0%	184	180	Above +
8		180	180	Lateral box hops, agility drills

Note: This progression is adapted from multiple current neuromuscular training protocols for injury prevention. Twice-weekly sessions were separated by at least 48 hours. Progression to a lower body weight support level was determined by tolerance as described in Table 2.
*Body weight support, or delivered vertical force expressed as the percentage of body weight.
†Contact is defined as an instance of landing or changing direction on the surgical leg, eg. landing a hop, landing a jump, or cutting/pivoting on surgical side. The number of contacts listed is the actual number of contacts performed by the subject during that session.

Figure 4. Illustration of body weight support system with harness.



A, 15 m elastic tubes stretched over approximately 76 m around pulleys, redirected upward toward final pulleys. B, final elastic element to which appropriate tubes (A) may be attached. C, final conjoined pulleys. D, 2.44 m. tensioned steel rod upon which top pulley of (C) can roll. E, hollow core aluminum yoke. F, free-sliding webbing. G, 3mm neoprene shorts customized to allow movement without sliding.

Figure 5. Subject performing lateral barrier hops in body weight support system with 20% body weight support.

The initial training was begun at a BWS level of 30%, wherein a near-constant vertical force equal to 30% of the subject's body weight was exerted at the center of mass. Previous work determined that between 20% and 30% BWS, VGRF decreased to levels approximately those of distance running without intrinsically changing lower extremity kinematics or relative joint kinetics.[61] The level of BWS was decreased every two weeks, from 30% to 20% to 10%, per tolerance to activity. The final two weeks of training were performed without BWS. Training volume was tracked via contacts, defined as the number of times the involved leg hit the ground and/or generated a directional change as in cutting. With BWS, higher contact counts were appropriate given the decreased VGRF. Interestingly, the subject was able to complete more contacts at the 20% and 10% BWS levels. During the initial phases of training, even with 30% BWS, she required extensive cueing to perform each task correctly. She also required more rest between sets in the first two weeks.

All other training parameters progressed over time as well. Feedback progressed from immediate visual, verbal, and tactile specific knowledge of results, to delayed verbalization of perceived performance. Cueing was geared toward positive reward throughout training, to reinforce desired behaviors (increased knee flexion, soft landing, upright posture)[36,62] rather than punishing undesired behaviors (straight knee, stiff landing, bending at the waist). The subject was cued primarily with an external attentional focus (eg, "try to sit down in a chair during landing"), with an internal focus as needed but not preferred (eg, "land with your knees bent").[63,64] Practice patterning progressed from blocked practice of each skill (vertical, lateral, sagittal, rotational jumping, and vertical, lateral, sagittal hopping) to serial practice and then random practice over time. Sport specific activities were introduced in week five and continued to progress through week eight, emphasizing dual task performance. For example, initially the subject performed jumps while holding a basketball. She progressed to catching and throwing the ball during landing, and then to dribbling during cutting and hopping, as well as performing a layup and landing appropriately.

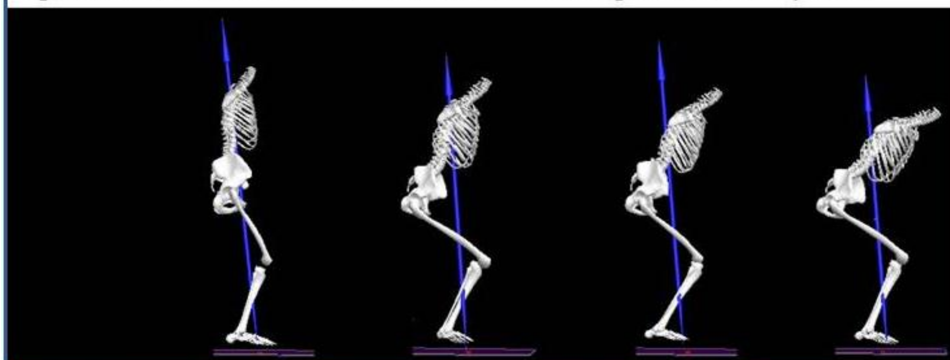
Outcome

The subject underwent re-testing mid-training, post-training, and again after eight weeks without supervised training for retention testing (**FIGURE 1**). All parts of the initial examination were performed, including administration of the IKDC and ACL-RSI, effusion testing, knee flexor and extensor strength testing, and biomechanical analysis of the single leg landing task.

The subject’s subjective functional level as measured by the IKDC improved throughout training to 95% (**FIGURE 2**). A change score of more than 20 points has a specificity of 0.84 for perceived improvement.[65] Since the change in the subject's IKDC score was 28 points, it is likely that she considered her condition improved. Her confidence in her knee’s performance as measured by the ACL-RSI increased to 84% (**FIGURE 2**). Muller et al[54] found that people that returned to sport had an average ACL-RSI score of 76.8%. She maintained her increased level of function and improved psychological readiness for sport over the two-month retention period. Six months following the conclusion of BWS training, the subject reported that she had progressed to running over six miles without knee pain. At the end of the training period, she reported that she had been playing basketball without consideration of her knee.

The subject's strength symmetry improved slightly throughout the training period. Further improvements in strength symmetry were made through the retention period; at the retention testing session, she demonstrated equal strength compared with the nonsurgical side (**TABLE 2**). She presented without effusion at all follow-up testing sessions, and her PROM remained symmetrical. Her VGRF in landing decreased by 0.5 BW through the training and retention periods (**FIGURE 3**). Her peak knee flexion in landing increased by 31° within the first four weeks, then maintained at the same approximate level of peak flexion. Peak hip flexion also increased through training, and continued to increase over the retention period. Ankle dorsiflexion during landing remained approximately the same with training.

Figure 3. Kinematic and kinetic measures over training and retention periods



Measure	Initial	Mid-Training	Post-Training	Retention
VGRF	3.6 N/kg	3.4 N/kg	2.6 N/kg	2.9 N/kg
Hip Angle	41°	85°	71°	89°
Moment	2.3 Nm/kg	4.8 Nm/kg	2.5 Nm/kg	3.2 Nm/kg
Knee Angle	49°	79°	76°	75°
Moment	1.3 Nm/kg	1.8 Nm/kg	1.9 Nm/kg	1.9 Nm/kg
Ankle Angle	21°	25°	27°	20°
Moment	2.1 Nm/kg	1.7 Nm/kg	1.8 Nm/kg	1.7 Nm/kg

*VGRF, vertical ground reaction force.
†Mid-training testing occurred at week 4 of training. Post-training testing occurred after full 8 week training period. Retention testing occurred after 8 weeks without training or contact with the investigators.

DISCUSSION

In this case report, BWS was used to modify an evidence-based jump training protocol to mitigate the inherently high intensity of jump training, allowing the subject to both increase training volume and target movement deficits in accordance with motor learning principles. Additionally, BWS decreased the perceived threat of landing, thereby decreasing apprehension. The current findings demonstrate that successful retraining of athletic tasks is possible in a subject with a history of ACL reconstruction and knee dysfunction. In particular, high volume training with BWS improved subjective outcomes, strength symmetry, and mechanical performance. Retention of these improvements after 8 weeks without training suggests that the new landing strategy had become a habitual pattern.

Chmielewski et al[17] have documented high fear of movement (or kinesiophobia) in people who have injured their ACL and undergone ACL reconstruction. Recent reviews by Ardern et al[18,66] have shown that psychological factors such as fear of movement and lack of confidence in the surgical knee play large roles in whether an athlete returns to their original level of activity after ACL reconstruction. However, no previous studies have demonstrated the ability to decrease post-surgical fear and increase confidence with physical training. This subject's gains in confidence and function with gradually increasing exposure to plyometric activity are consistent with those of graded exposure for psychologically driven activity limitation.[41]

Following ACL reconstruction, many patients are released to sport based solely on the elapsed time since surgery.[67] However, the intensity of the fear stimulus in returning to play may be psychologically traumatic.[5,18] Repeated exposure to the high intensity stimulus may not be enough to counteract fear behaviors. The current subject had undergone a six-month period of rehabilitation following her ACL reconstruction seven years previously, and had returned to playing recreational basketball. Regardless, she was unable to regain functional mechanics and confidence in her knee. However, by gradually performing sport-specific activities in a safe environment, she was able to increase in confidence and function simultaneously. Her success demonstrates that interventions for motor skill re-training can be effective and even necessary, regardless of the time since surgery.

As expected, the subject increased peak knee flexion and decreased peak VGRF during landing, and continued to improve in these measures over the entire training period. She demonstrated relative retention of her improvement in mechanics after eight weeks without training or contact with the investigators. Her strength symmetry also improved, which may have contributed to her mechanical improvements. Recent evidence has shown an effect of plyometric training on maximal volitional strength.[68] However, Herman et al[69] found no significant differences in kinematic and kinetic variables during a stop jump task before and after a nine-week strengthening program. Therefore, rather than strength gains affecting habitual mechanics, the opposite effect is posited. As the subject's mechanics improved, her strength increased. Indeed, her continued increase in strength over the retention period without any training intervention further supports the hypothesis that habitual changes in mechanics led to strength gains.

Further contribution to her mechanical improvements may have come from healing of the subject's reported bone bruise, which had been demonstrated by MRI two months prior to her initial examination. The treating therapist was unable to obtain an imaging report to differentiate between subperiosteal hematoma or bone marrow edema. However, the time from the subject reported MRI to her laboratory examination was 7.5 months, during which time either problem would be likely to heal. At the time of laboratory examination, her mechanics in single leg landing remained demonstrably poor. Improvements in her mechanics in the next to months are most likely due to intervention, rather than healing of the bone bruise. The presence of a bone bruise does suggest a chronically insufficient use of the muscular shock absorbers and inappropriate impact force transmission and trauma to bony structures. The subject had previously been unable to modify her movement patterns without direct intervention into her mechanical behaviors, in keeping with evidence demonstrating a high risk for poor long-term outcomes following ACL reconstruction.[7-10,12,20] The current case report demonstrates that chronically dysfunctional movement patterns can be changed through direct intervention in the form of task-specific training, even with extensive time since the original injury and rehabilitation.

Prior efforts to mitigate loading during sporting tasks have utilized three basic methods: aquatic therapy, plyometric leg press, and treadmill mounted systems such as the AlterG.[44,45,47,70] Indeed, the subject in this case study was initially treated via a plyometric leg press (the Total Gym®) to avoid excessive compression due to her verbal report of a bone bruise. All of these methods suffer from a lack of specificity to task training. The aquatic environment does support the center of mass and provides effective mitigation of load according to the level of body submersion. However, speeds of body and limb movement differ substantially from standard exercise due to hydraulic and drag forces, which can also create abnormal shear torques through joints due to turbulence and pressure gradients.[47] Additionally, while jump landing is primarily an eccentric task, the aquatic environment allows nearly exclusive concentric activity.[47] Alternatively, a plyometric leg press can allow patients to practice jumping or hopping in place. While this does, again, reduce the amount of compression load through the limb, gravitational forces continue to be felt by the body. During a jump on a plyometric leg press positioned at 45 degrees or parallel to the ground (as with a Pilates Reformer), for example, a person must utilize the hip flexors to maintain the leg in a position for landing. Again, specificity is lost. These applications are also confined to a small, solid landing platform, disallowing any sport specificity. The BWS system utilized in this case allows near total specificity of movement as well as support during cutting, pivoting, and other sport specific tasks.

While this case study focused on a young athlete with chronic deficits in absorption of VGRFs in landing, BWS may be useful at earlier times in the healing process and in the treatment of other functional deficits in other populations. For example, BWS may allow early and intensive retraining of landing mechanics following ACL reconstruction prior to return to sport. Athletes returning to closed-chain activity following cartilage or meniscal repair may also benefit from a more specific training environment. Performance of a full squat or sit to stand involves complex weight shifting and balance along with force production. Performance of a full squat in an aquatic environment changes the amount of support offered by the water, and a leg press machine does not challenge the balance component of the squat task. Stair climbing and descent frequently remain problematic for people with total knee arthroplasty,[71] including many older athletes. It is difficult to decrease the intensity of the activity without decreasing the height of the stair and thereby reducing task specificity.

The current case report also provides an example of the relative importance of volume and intensity in retraining complex movement patterns. As when retraining gait patterns following neurological insult,[42,43] high training volume may be necessary to attain appropriate neuromuscular adaptation. In rats with spinal cord transection, 1000 steps per training session improved stepping quality more than 100 steps per session.[72] In healthy humans performing upper extremity reaching task, 600 repetitions were required for learning.[73] The degree to which the training intensity must be specific to single limb jumping and landing is unknown and should be explored further. The training protocol as developed accounted for specificity of training intensity by gradually weaning the subject from BWS, but it is unknown whether she would have been able to make equivalent changes in her movement patterns through high-intensity training with the requisite lower training volumes.

The outcomes of this case study are not generalizable to other patients due to the nature of the single subject design. Further studies are needed to elucidate the differences in outcomes between high-intensity/low-repetition and high-repetition/low-intensity training paradigms in larger samples. Additionally, the measurement and treatment methods described may not be available in a typical outpatient physical therapy clinic. The eight-camera motion analysis system utilized here is able to capture and visualize kinetic outcomes, allowing improved identification of specific functional impairments. While kinetic analysis is generally unavailable in most clinics, video analysis may provide adequate kinematic information. Further, though the space requirements and expense of a seated dynamometer may be prohibitive to its clinical use, handheld dynamometry may allow improved testing of strength. Tests and measures adequately sensitive to the specific patient population should be more consistently used in clinic. The BWS system is also not currently available for widespread use due to its custom design. However, the components of the BWS system are inexpensive and relatively easily installed, given the potential for safe ceiling suspension.

CONCLUSIONS

In sum, a low-intensity, high-volume training intervention using BWS during plyometric training was able to generate positive changes in both mechanical and psychological impairments in a single subject with chronic dysfunction following ACL reconstruction. Further research into the mechanical, neuromuscular, psychological, and functional changes possible with plyometric training is needed, particularly in a population with poorer-than-expected long-term outcomes.

REFERENCES

1. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *The American journal of sports medicine.* 2014;42(10):2363-2370.

2. Wilk KE, Reinold MM, Hooks TR. Recent advances in the rehabilitation of isolated and combined anterior cruciate ligament injuries. *The Orthopedic clinics of North America.* 2003;34(1):107-137.
3. Fitzgerald GK, Piva SR, Irrgang JJ. A modified neuromuscular electrical stimulation protocol for quadriceps strength training following anterior cruciate ligament reconstruction. *The Journal of orthopaedic and sports physical therapy.* 2003;33(9):492-501.
4. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *The Journal of orthopaedic and sports physical therapy.* 2012;42(7):601-614.
5. Ardern CL, Taylor NF, Feller JA, Webster KE. Fear of re-injury in people who have returned to sport following anterior cruciate ligament reconstruction surgery. *J Sci Med Sport.* 2012;15(6):488-495.
6. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *The American journal of sports medicine.* 2012;40(1):41-48.
7. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery: two-thirds of patients have not returned by 12 months after surgery. *The American journal of sports medicine.* 2011;39(3):538-543.
8. Holm I, Oiestad BE, Risberg MA, Aune AK. No difference in knee function or prevalence of osteoarthritis after reconstruction of the anterior cruciate ligament with 4-strand hamstring autograft versus patellar tendon-bone autograft: a randomized study with 10-year follow-up. *The American journal of sports medicine.* 2010;38(3):448-454.
9. von Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis.* 2004;63(3):269-273.
10. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *The American journal of sports medicine.* 2010;38(11):2201-2210.
11. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.
12. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther.* 2000;80(3):251-260.
13. Chmielewski TL, Hurd WJ, Rudolph KS, Axe MJ, Snyder-Mackler L. Perturbation training improves knee kinematics and reduces muscle co-contraction after complete unilateral anterior cruciate ligament rupture. *Phys Ther.* 2005;85(8):740-749; discussion 750-744.
14. Deneweth JM, Bey MJ, McLean SG, Lock TR, Kolowich PA, Tashman S. Tibiofemoral joint kinematics of the anterior cruciate ligament-reconstructed knee

during a single-legged hop landing. *The American journal of sports medicine.* 2010;38(9):1820-1828.
15. Gokeler A, Hof AL, Arnold MP, Dijkstra PU, Postema K, Otten E. Abnormal landing strategies after ACL reconstruction. *Scand J Med Sci Sports.* 2010;20(1):e12-19.
16. Orishimo KF, Kremenic IJ, Mullaney MJ, McHugh MP, Nicholas SJ. Adaptations in single-leg hop biomechanics following anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(11):1587-1593.
17. Chmielewski TL, Zeppieri G, Jr., Lentz TA, et al. Longitudinal changes in psychosocial factors and their association with knee pain and function after anterior cruciate ligament reconstruction. *Phys Ther.* 2011;91(9):1355-1366.
18. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *The American journal of sports medicine.* 2013;41(7):1549-1558.
19. Mizner R, Mahlum BT. Clinical Utility of an Injury Specific Psychological Survey for Long-Term ACLR Outcomes. Combined Sections Meeting of the APTA. Platform Presentationin the Sports Section. San Diego, CA. *Journal of Orthopaedic and Sports Physical Therapy.* 2013;Jan 43(1):Supplement.
20. Salmon L, Russell V, Musgrove T, Pinczewski L, Refshauge K. Incidence and risk factors for graft rupture and contralateral rupture after anterior cruciate ligament reconstruction. *Arthroscopy.* 2005;21(8):948-957.
21. Paterno MV, Schmitt LC, Ford KR, et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *The American journal of sports medicine.* 2010;38(10):1968-1978.
22. Ratzlaff CR, Koehoorn M, Cibere J, Kopec JA. Is lifelong knee joint force from work, home, and sport related to knee osteoarthritis? *Int J Rheumatol.* 2012;2012:584193.
23. Chmielewski TL, Trumble TN, Joseph AM, et al. Urinary CTX-II concentrations are elevated and associated with knee pain and function in subjects with ACL reconstruction. *Osteoarthritis and cartilage / OARS, Osteoarthritis Research Society.* 2012;20(11):1294-1301.
24. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *The American journal of sports medicine.* 2013;41(1):216-224.
25. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(8):859-879.
26. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. *J Athl Train.* 2004;39(1):24-31.
27. Dai B, Herman D, Liu H, Garrett WE, Yu B. Prevention of ACL injury, part II: effects of ACL injury prevention programs on neuromuscular risk factors and injury rate. *Res Sports Med.* 2012;20(3-4):198-222.

28. Sugimoto D, Myer GD, Bush HM, Klugman MF, Medina McKeon JM, Hewett TE. Compliance with neuromuscular training and anterior cruciate ligament injury risk reduction in female athletes: a meta-analysis. *J Athl Train.* 2012;47(6):714-723.
29. Hurd WJ, Chmielewski TL, Snyder-Mackler L. Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. *Knee Surg Sports Traumatol Arthrosc.* 2006;14(1):60-69.
30. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* 2005;39(12):932-938.
31. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *Journal of strength and conditioning research / National Strength & Conditioning Association.* 2012;26(8):2272-2292.
32. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *The American journal of sports medicine.* 2013;41(1):203-215.
33. Sugimoto D, Myer GD, McKeon JM, Hewett TE. Evaluation of the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a critical review of relative risk reduction and numbers-needed-to-treat analyses. *Br J Sports Med.* 2012;46(14):979-988.
34. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *The Journal of orthopaedic and sports physical therapy.* 2006;36(5):308-319.
35. Vaczi M, Tollar J, Meszler B, Juhasz I, Karsai I. Short-term high intensity plyometric training program improves strength, power and agility in male soccer players. *J Hum Kinet.* 2013;36:17-26.
36. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *The American journal of sports medicine.* 1996;24(6):765-773.
37. Kerr AL, Cheng SY, Jones TA. Experience-dependent neural plasticity in the adult damaged brain. *Journal of communication disorders.* 2011;44(5):538-548.
38. Luft AR, Buitrago MM. Stages of motor skill learning. *Molecular neurobiology.* 2005;32(3):205-216.
39. Wertli MM, Rasmussen-Barr E, Weiser S, Bachmann LM, Brunner F. The role of fear avoidance beliefs as a prognostic factor for outcome in patients with nonspecific low back pain: a systematic review. *The spine journal : official journal of the North American Spine Society.* 2014;14(5):816-836 e814.
40. Wertli MM, Rasmussen-Barr E, Held U, Weiser S, Bachmann LM, Brunner F. Fear-avoidance beliefs-a moderator of treatment efficacy in patients with low back pain: a systematic review. *The spine journal : official journal of the North American Spine Society.* 2014;14(11):2658-2678.
41. George SZ, Wittmer VT, Fillingim RB, Robinson ME. Comparison of graded exercise and graded exposure clinical outcomes for patients with chronic low

back pain. *The Journal of orthopaedic and sports physical therapy.* 2010;40(11):694-704.

42. Mehrholz J, Pohl M, Elsner B. Treadmill training and body weight support for walking after stroke. *The Cochrane database of systematic reviews.* 2014;1:CD002840.
43. Wessels M, Lucas C, Eriks I, de Groot S. Body weight-supported gait training for restoration of walking in people with an incomplete spinal cord injury: a systematic review. *Journal of rehabilitation medicine.* 2010;42(6):513-519.
44. Moore MN, Vandenakker-Albanese C, Hoffman MD. Use of partial body-weight support for aggressive return to running after lumbar disk herniation: a case report. *Archives of physical medicine and rehabilitation.* 2010;91(5):803-805.
45. Saxena A, Granot A. Use of an anti-gravity treadmill in the rehabilitation of the operated achilles tendon: a pilot study. *The Journal of foot and ankle surgery : official publication of the American College of Foot and Ankle Surgeons.* 2011;50(5):558-561.
46. Takacs J, Leiter JR, Peeler JD. Novel application of lower body positive-pressure in the rehabilitation of an individual with multiple lower extremity fractures. *Journal of rehabilitation medicine.* 2011;43(7):653-656.
47. Haupenthal A, Ruschel C, Hubert M, de Brito Fontana H, Roesler H. Loading forces in shallow water running in two levels of immersion. *Journal of rehabilitation medicine.* 2010;42(7):664-669.
48. Hislop H, Montgomery J, Connolly B, Daniels L. *Daniels and Worthingham's muscle testing: Techniques of manual examination.* Philadelphia, PA: W.B. Saunders; 1995.
49. Elias AR, Hammill CD, Mizner RL. Changes in Quadriceps and Hamstring Co-contraction Following Landing Instruction in Patients With Anterior Cruciate Ligament Reconstruction. *The Journal of orthopaedic and sports physical therapy.* 2015:1-27.
50. Harty CM, DuPont CE, Chmielewski TL, Mizner RL. Intertask comparison of frontal plane knee position and moment in female athletes during three distinct movement tasks. *Scand J Med Sci Sports.* 2011;21(1):98-105.
51. Grevnerts HT, Terwee CB, Kvist J. The measurement properties of the IKDC-subjective knee form. *Knee Surg Sports Traumatol Arthrosc.* 2014.
52. Ebrahimzadeh MH, Makhmalbaf H, Golhasani-Keshtan F, Rabani S, Birjandinejad A. The International Knee Documentation Committee (IKDC) Subjective Short Form: a validity and reliability study. *Knee Surg Sports Traumatol Arthrosc.* 2014.
53. Webster KE, Feller JA, Lambros C. Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine.* 2008;9(1):9-15.
54. Muller U, Kruger-Franke M, Schmidt M, Rosemeyer B. Predictive parameters for return to pre-injury level of sport 6 months following anterior cruciate ligament reconstruction surgery. *Knee Surg Sports Traumatol Arthrosc.* 2014.

55. Sturgill LP, Snyder-Mackler L, Manal TJ, Axe MJ. Interrater reliability of a clinical scale to assess knee joint effusion. *The Journal of orthopaedic and sports physical therapy.* 2009;39(12):845-849.
56. Mizner RL, Petterson SC, Snyder-Mackler L. Quadriceps strength and the time course of functional recovery after total knee arthroplasty. *The Journal of orthopaedic and sports physical therapy.* 2005;35(7):424-436.
57. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *The Journal of orthopaedic and sports physical therapy.* 2008;38(6):353-361.
58. Bohannon RW. Manual muscle testing: does it meet the standards of an adequate screening test? *Clin Rehabil.* 2005;19(6):662-667.
59. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part I: neuromuscular screening methods to identify high ACL injury risk athletes. *Journal of strength and conditioning research / National Strength & Conditioning Association.* 2012;26(8):2265-2271.
60. Anderson AF, Irrgang JJ, Kocher MS, Mann BJ, Harrast JJ, International Knee Documentation C. The International Knee Documentation Committee Subjective Knee Evaluation Form: normative data. *The American journal of sports medicine.* 2006;34(1):128-135.
61. Elias AR. The effect of body weight support on kinetics and kinematics of a repetitive plyometric task. *Journal of Applied Biomechanics.* 2015;IN REVIEW.
62. McNair PJ, Prapavessis H, Callender K. Decreasing landing forces: effect of instruction. *Br J Sports Med.* 2000;34(4):293-296.
63. Benjaminse A, Gokeler A, Dowling AV, et al. Optimization of the anterior cruciate ligament injury prevention paradigm: novel feedback techniques to enhance motor learning and reduce injury risk. *The Journal of orthopaedic and sports physical therapy.* 2015;45(3):170-182.
64. Gokeler A, Benjaminse A, Welling W, Alferink M, Eppinga P, Otten B. The effects of attentional focus on jump performance and knee joint kinematics in patients after ACL reconstruction. *Physical therapy in sport : official journal of the Association of Chartered Physiotherapists in Sports Medicine.* 2015;16(2):114-120.
65. Irrgang JJ, Anderson AF, Boland AL, et al. Responsiveness of the International Knee Documentation Committee Subjective Knee Form. *The American journal of sports medicine.* 2006;34(10):1567-1573.
66. Ardern CL, Taylor NF, Feller JA, Webster KE. A systematic review of the psychological factors associated with returning to sport following injury. *Br J Sports Med.* 2012.
67. Petersen W, Zantop T. Return to play following ACL reconstruction: survey among experienced arthroscopic surgeons (AGA instructors). *Archives of orthopaedic and trauma surgery.* 2013;133(7):969-977.
68. Behrens M, Mau-Moeller A, Mueller K, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport.* 2015.

69. Herman DC, Weinhold PS, Guskiewicz KM, Garrett WE, Yu B, Padua DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *The American journal of sports medicine.* 2008;36(4):733-740.
70. Kluitenberg B, Bredeweg SW, Zijlstra S, Zijlstra W, Buist I. Comparison of vertical ground reaction forces during overground and treadmill running. A validation study. *BMC musculoskeletal disorders.* 2012;13:235.
71. Zeni JA, Jr., Snyder-Mackler L. Early postoperative measures predict 1- and 2-year outcomes after unilateral total knee arthroplasty: importance of contralateral limb strength. *Phys Ther.* 2010;90(1):43-54.
72. Cha J, Heng C, Reinkensmeyer DJ, Roy RR, Edgerton VR, De Leon RD. Locomotor ability in spinal rats is dependent on the amount of activity imposed on the hindlimbs during treadmill training. *Journal of neurotrauma.* 2007;24(6):1000-1012.
73. Fine MS, Thoroughman KA. Motor adaptation to single force pulses: sensitive to direction but insensitive to within-movement pulse placement and magnitude. *Journal of neurophysiology.* 2006;96(2):710-720.

CLINICAL EFFECTIVENESS OF JUMP TRAINING AUGMENTED WITH BODY WEIGHT SUPPORT FOLLOWING ACL RECONSTRUCTION: A RANDOMIZED PRAGMATIC TRIAL

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The project was reviewed and approved by the
Institutional Review Board of the University of Montana.

Background: Abnormally limited knee flexion and increased co-contraction of the quadriceps and hamstrings during jump landing are thought to contribute to decreased functional outcomes following anterior cruciate ligament (ACL) reconstruction. The effective dosage of jump training to improve mechanical and neuromuscular deficits following ACL reconstruction is unknown.
Hypothesis/Purpose: We hypothesize that jump training will improve patient-reported function and biomechanical outcomes, and that higher repetition training augmented by body weight support (BWS) will result in improved retention of functional, mechanical, and neuromuscular gains.
Study Design: Randomized Pragmatic Clinical Trial
Methods: Nineteen subjects, averaging 18 months post-ACL reconstruction, with impaired function as measured by the International Knee Documentation Committee (IKDC) questionnaire, poor performance as measured by limb symmetry in a single leg hop for distance (SLHD), poor landing mechanics as measured by knee flexion during single leg landing, and poor neuromuscular coordination as measured by a surface electromyography-generated co-contraction index in single leg landing were randomly assigned to one of two training groups: jump training with normal body weight (JTBW), and jump training with BWS (JTBWS). BWS allowed higher repetition of training activities over the 8 week training period. Effusion grading throughout training assessed joint tolerance. Outcomes were compared pre- and post-training. Retention of gains was measured 8 weeks following completion of training. Patient-reported outcomes, SLHD, kinetic, and kinematic data were analyzed with two-way ANOVAs with effects of time and group. Co-contraction indices were compared utilizing mixed-effects modeling with random effect of subject.
Results: There were significant effects of time during the training phase (weeks 0-8) for all outcome measures, but no effect of group. All measures were retained over time in both groups. The JTBW group had a higher probability of effusion over the training period.
Conclusion: Jump training effectively mitigates risk factors for second injury and osteoarthritis in patients following ACL reconstruction. Gains in mechanical and neuromuscular coordination deficits are reflected in lasting improvements in function and performance. Higher repetition with BWS did not improve retention, but may be safer for articular surfaces.
Clinical Relevance: While included in many return-to-sport recommendations, jump training has not to this point been investigated in a post-surgical population. Jump training is an effective intervention for people with poor outcomes following ACL reconstruction, and supporting body weight may lessen joint reactivity.
Key Terms: Jump training, biomechanics, single leg landing, neuromuscular coordination

Introduction

Injury of the anterior cruciate ligament (ACL) is one of the most prevalent knee injuries in athletes who participate in cutting and pivoting sports.[1] Modern reconstruction techniques with accelerated rehabilitation protocols consistently resolve anterior knee laxity and rapidly return patients to physical activity.[2] However, over half of the patients who undergo ACL reconstruction will show radiographic evidence of knee osteoarthritis within 10 to 15 years after surgery.[3] Additionally, in those who do return to sport, the rates of incurring a second ACL injury are as high as 1 in 4 patients.[4] As a result, a large cohort of patients who have ACL reconstruction can expect decades of arthritic pain and disability during their lifetime, contributing to a significant public health problem.[5]

A growing body of evidence suggests that the ACL reconstructed knee commonly exhibits abnormal mechanical and neuromuscular behaviors during the tasks in which the knee is most frequently injured, such as landing from a jump.[6-8] The operated knee generally continues to exhibit decreased knee flexion during weight acceptance with reduced knee flexion moments in comparison to the uninvolved limb.[7] Landing from a jump with large landing forces and limited knee motion is common after ACL reconstruction, and musculoskeletal modeling has found it increases strain on the ACL.[9] The operated limb also responds to jump landing with co-contraction of the knee flexors and extensors compared to the uninvolved side and healthy peers.[6,10,11] In vivo knee modeling suggests co-contraction during landing is associated with increased knee compressive forces compared to healthy limbs.[10] Excessive loading is known to play a causative role in knee osteoarthritis.[12] Thus, mechanical and neuromuscular limitations contribute to both re-injury and osteoarthritis risk.

Recent work has established that brief instruction in jump landing technique shows promise as a means to improve force absorption and decrease co-contraction following ACL reconstruction on a short-term basis.[11,13] Restoring the force attenuating capacity of the ACL reconstructed limb could therefore decrease re-injury rates and mitigate arthritic changes. The effects of extended jump training following ACL reconstruction, however, is not known and represents a gap in the current evidence base.

The initiation of a jump training program following ACL reconstruction requires caution as possible increases in cartilage degradation can occur in an already vulnerable joint.[14] Because of this, low repetition of jump training activity in healthy athletes with uninjured knees is frequently recommended due to high ground reaction forces, and concern for the articular health of the joint.[15] Retraining efforts may also be self-limited by patients who restrict their knee loading during landing due to fear of injury or lack of confidence in the operated limb.[16] Collectively, these considerations can be barriers to effective dosing of jump training regimens and a reason for low effect sizes and poor retention of jump training interventions, even in healthy athletes.

Important tenants in motor learning highlight the need for a high number of repetitions of a task to improve retention of a motor skill.[17] Only one study to date has compared the effects of varying doses (e.g., repetition or volume) in plyometric training 4-6 months post-ACL reconstruction.[18] Higher volume plyometric training resulted in greater improvements in functional performance, such as single leg hop for distance, than lover volume training.[18] Biomechanical and neuromuscular performance measures such as knee flexion, vertical ground reaction forces (VGRF), and co-contraction were not measured, however. Additionally, retention of these improvements was not measured and the reported training dosage in the high volume group was lower than what is theorized to generate lasting change.

Managing clinically meaningful doses of jump training is challenging. For example, increased repetition is generally accompanied by decreased intensity. However, reducing intensity during jump landing is problematic as the current recommendations to lower the height of the jump still induce large and rapid limb loading when landing.[15] By utilizing body weight support (BWS), the intensity of jump landing tasks can be decreased while still allowing normal kinematic and kinetic behaviors, thereby allowing increased repetition of training.[19]

The purpose of this study is therefore two-fold: 1) to examine the impact of an extended jump training program on patient-reported function and biomechanical measures; and 2) to determine whether a high repetition program with decreased intensity via BWS will improve functional, mechanical, and neuromuscular outcomes. We hypothesize that jump landing training, whether relatively low or high repetition, will improve outcomes, but that higher repetition training will result in improved retention of functional, mechanical, and neuromuscular gains. Further, we posit that the group trained under body weight support conditions will exhibit greater training tolerance as assessed by their knee effusion status.

METHODS

Trial design

The study was designed as a randomized pragmatic parallel trial to assess the efficacy of high-repetition jump training with BWS as compared to a best practice jump training program. Participants underwent an initial screening evaluation to determine appropriateness for intervention following ACL reconstruction. Those individual participants with functional and biomechanical deficits were considered in need of intervention, and were randomly assigned to one of two intervention groups: jump training under normal body weight conditions (JTBW) and jump training augmented by a custom BWS system (JTBWS). Follow-up testing occurred mid-intervention and post-intervention, and retention testing occurred at least 8 weeks post-intervention. All testing and intervention protocols were approved by the University of Montana Internal Review Board. All participants provided written informed consent to initial screening testing and further training. The trial is registered at ClinicalTrials.gov, registration number NCT02148172. Active recruitment began in February 2014 and continued through March 2015. Training and follow-up testing continued through July 2015.

Participants

Participants were recruited for initial screening by flyer advertisement postings on the University of Montana campus, by advertising in the community outside of campus, and by word-of-mouth from local physical therapists and orthopedic surgeons. Participants were eligible for screening if they were between 6 and 48 months post-ACL reconstruction, between the ages of 12 and 35, had been cleared for sports participation by their surgeon, and actually participated in recreational or competitive sports at a Tegner Activity Scale level greater than 4.

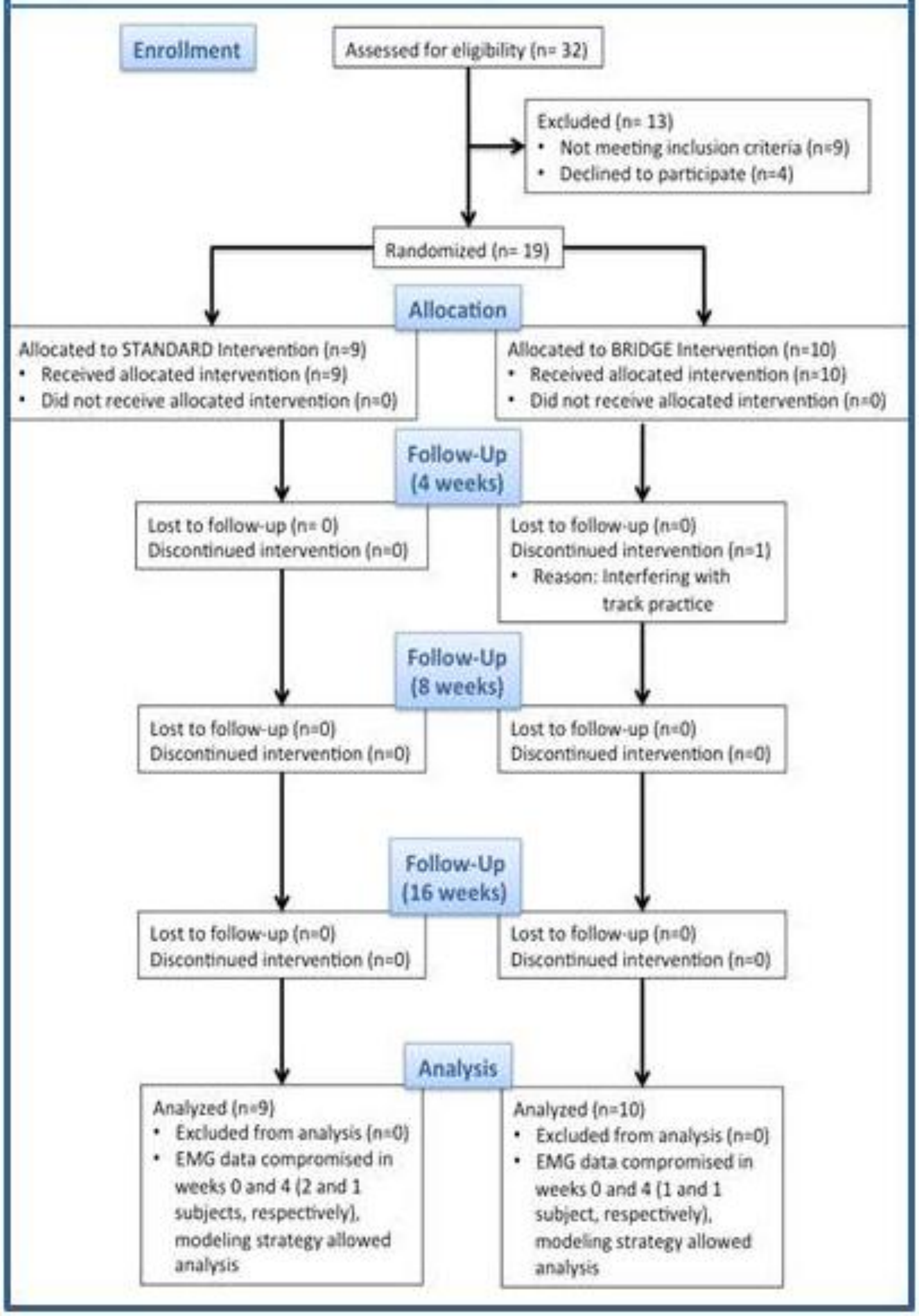


Figure 1. CONSORT Diagram

Exclusion criteria for initial screening included bilateral ACL injury or revision to the original ACL reconstruction, a history of posterior cruciate ligament injury, or a history of lower extremity injury or health condition that limited activities of daily living within the previous 6 months. Potential subjects would also be excluded if they weighed more than 136 kilograms as the BWS system provided a maximal dose of BWS of 40 kilograms.

Participants met eligibility criteria for randomization into treatment groups based on poor IKDC score, SLHD limb symmetry, or peak knee moment during single leg land. Poor scores were defined as falling further than 1 standard deviation below the mean, as determined by a database of athletes meeting the same inclusion and exclusion criteria previously tested[11] or from previously published return to sport standards.[20] Effectively, scores of <75% on the IKDC, a limb symmetry index <75% in a single leg hop for distance test, or a peak knee moment <2.3 body weights (BW) and <80% of the nonsurgical side during a single leg landing task were defined as outcomes that may benefit from intervention.

Participants meeting one or more of the eligibility criteria were offered placement into the clinical trial. Upon acceptance, each participant was randomly allocated to one of two treatment groups as detailed in the CONSORT Flow Diagram (Figure 1).

Testing procedures occurred in the following order: administration of the International Knee Documentation Committee Subjective Knee Form (IKDC); 5 minute treadmill walking warm-up; placement of electromyography electrodes; maximal voluntary isometric contraction and strength testing; placement of retroreflective markers; completion of the single leg hop for distance (SLHD) test; static standing subject calibration; and biomechanical analysis of hopping tasks as detailed below.

Setting

All testing and training took place in the Movement Science Laboratory on the University of Montana campus. Participants allocated to the JTBWS condition completed their training utilizing the custom BWS system described below. Participants allocated to the JTBW condition completed their training in the same location, but with the BWS system removed from the area. All training was completed on an individual basis with a licensed physical therapist.

Outcomes

Patient-Reported and Performance-Based Functional Outcomes

The IKDC is a validated and frequently utilized knee-specific patient-reported functional outcome measure documenting symptoms as well as participation in daily functional and sports activities.[21] Normative data allows documentation of function as a percentile score.[22] The IKDC is also less subject to a ceiling effect in an active population, and it's use is consistent with clinical practice guidelines.[21]

The SLHD is a commonly used reliable and valid performance-based outcome measure.[23,24] Testing was completed in accordance with previously published methodology.[24] Limb symmetry was expressed as the ratio of the average distance hopped by the operated limb to the average distance hopped by the non-operated limb.[23]

Biomechanical Outcomes

Electromyographic, kinematic, and kinetic data were obtained during the landing phase of a single-leg landing task as previously described.[11] Specific outcomes of particular interest included peak sagittal lower extremity joint angles and moments as well as co-contraction of the quadriceps and hamstrings during the weight acceptance phase of landing. The single-leg landing task was chosen since the mechanism of a non-contact ACL injury typically occurs during single leg landing.[25] Additionally, a single-leg task reduces the degrees of freedom available for compensatory movement patterning that might be possible in a double-leg task such as a drop vertical jump.

Electromyographic Testing

In preparation for electromyographic analysis of the single-leg landing task, knee flexor and extensor MVIC testing was performed in a seated position using a Kin-Com 125AP dynamometer (Chattanooga Group, Inc., Chattanooga, TN) employing previously published methods.[11,26] Muscle activation levels recorded with sEMG during the MVIC trial with the greatest torque produced were used for sEMG normalization during analysis of the single-leg landing task.

Muscle activation levels were recorded from the vastus lateralis (VL) and biceps femoris (BF) using a Bagnoli sEMG system (Delsys Inc., Boston, MA) interfaced with a VICON Nexus system (Oxford Metrics, Ltd., London, UK) with a 16-bit analog-digital converter as previously described.[11]

Using Visual 3D software (Visual 3D, Version 4.75.29, C-motion Inc., Rockville, Md), sEMG signals were bandpass filtered at 20-350 Hz and full-wave rectified before a linear envelope was created with a 10Hz low-pass phase corrected Butterworth filter. Electromyography signals were then normalized to the peak sEMG signal obtained during the peak MVIC trial, and normalized signal was used for analysis of co-contraction during the single leg landing task.

Instantaneous co-contraction was defined as the weighted ratio between hamstring and quadriceps activation, and the co-contraction index (CoI) as the integral of that function across the weight acceptance phase of landing:[27]

$$\int_{100\ ms\ before\ land}^{Peak\ knee\ flex} \frac{EMG_L}{EMG_H} * (EMG_L + EMG_H)$$

where EMG_L is the normalized activation of the less active muscle and EMG_H is the normalized activation of the more active muscle. This method combines estimations of relative recruitment of the quadriceps and hamstrings as well as the magnitude of co-contraction.[28] Both the co-contraction index and maximal instantaneous co-contraction were used as measures of muscle activation pattern.

Biomechanical Testing

Kinematic and kinetic data were obtained during landing tasks using the VICON Nexus motion capture system with 8 MXF40 cameras and a 400x600 mm force plate (AMTI, Watertown, MA) capturing ground reaction forces. Video data were sampled at 200 Hz; force place data were sampled at 1200 Hz and processed via previously published methodology.[11]

Retro-reflective markers (14 mm diameter) were placed per previous work to track the three-dimensional position of the feet, shanks, thighs, pelvis, and trunk.[11,26] A standing calibration was performed prior to completing the landing trials to identify joint centers with respect to each segment's coordinate system.

Joint kinematics were calculated using Euler angles, and joint kinetics were calculated with inverse dynamics using rigid body analysis through custom applications with Visual 3D software. Joint angles and moments were time normalized to 100 increments from 100 milliseconds prior to initial contact on the force place to peak knee flexion during landing (the weight acceptance phase) to enable the calculation of an ensemble average across trials for each subject, as the time between these events varied slightly within subject trials.

The full testing procedure was repeated after 4 weeks of training and again at completion of the full 8-week training course. Retention testing was performed after 8 weeks without contact with the researchers. The definition of events during landing was modified in the trained state to end at peak knee flexion or when the VGRF equaled 1 body weight, whichever came first: changes in the timing of knee bending in the trained state resulted in artificially extended landing phases according to the original definition of 100 msec prior to land to peak knee flexion. This new definition allowed comparison of integrated EMG between trials.

Table 1. Treatment session protocol, performed twice weekly for eight weeks.

Treatment Component	Specific Task	
Joint reaction check * **(for previous treatment)**	Knee pain rating on 1-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion	
Warm-up	5 minute treadmill walking (3-3.5 mph) High knee running Heel-to-gluteal running High kick walking Hip wrap walking with heel raise Lunge walking	
Jump Training	Contacts‡ – JTBW	Contacts‡ – JTBWS
Week 1	80-100	200-350
2		
3	80-160	250-500
4		
5	120-200	200-350
6		
7	120-200	120-200
8		
Cool-down	5 minute treadmill walking (3-3.5 mph) Quadriceps stretch (30 seconds) Hamstrings stretch (30 seconds) Calf stretch (30 seconds) Hip abductor stretch (30 seconds)	
Joint reaction check † **(for current treatment)**	Knee pain rating on 1-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion	

Adapted from intervention previously described in Elias (2015).
* If knee pain was >2 levels higher than previous treatment, treatment was delayed and the next treatment did not progress in repetition or intensity. If muscle soreness did not relieve during warm-up and visually compromised landing technique, treatment was delayed. If the stroke test graded at or above a 2+ effusion, treatment was delayed and the next treatment did not progress in repetition or intensity.
† If knee pain increased >2 levels during treatment, the next treatment did not progress in repetition or intensity. Muscle soreness and fatigue was noted for comparison to the next pre-treatment check. If the stroke test graded >1 level above the pre-treatment grade, the next treatment did not progress in repetition or intensity.
‡ Contact is defined as an instance of landing or changing direction on the surgical leg, eg. landing a hop, landing a jump, or cutting/pivoting on surgical side. The number of contacts listed is the actual number of contacts performed by the subject during that session.

Participant Outcome Rating

The Global Rating of Change (GROC) outcome measure was administered at each follow up testing session in addition to the IKDC. The GROC has been validated as a measure of patient-perceived outcomes.[29] Subjects rated the overall condition of their knee from the time they began treatment to each specified testing session on a 15-point scale with anchors of -7 (A very great deal worse), 0 (About the same), and 7 (A very great deal better).

Table 2. Jump training treatment progression protocol

	Phase	Contacts	Tasks
Jump Training – Normal Body Weight			
Week 1 **2**	Technique	80-100	Vertical jumps, lateral jumps, broad jumps, spinning jumps, split jumps, tuck jumps Stationary bounding
3 **4**	Fundamentals	80-160	Above + Triple Jumps, vertical hops, lateral hops
5 **6**	Performance	120-200	Above + Combination jumps, Lateral cutting, triple broad hops, box hops
7 **8**	Specificity	120-200	Above + Lateral box hops, agility drills
Jump Training – Body Weight Supported			
Week 1 **2**	30%	200-350	Vertical jumps, lateral jumps, broad jumps, spinning jumps, split jumps Vertical hops, lateral hops, broad hops
3 **4**	20%	250-500	Above + Triple broad hops, box hops, bounding
5 **6**	10%	200-350	Above + Combination jumps, Lateral cutting
7 **8**	0%	120-200	Above + Lateral box hops, agility drills

Note: This progression is adapted from multiple current neuromuscular training protocols for injury prevention. Twice-weekly sessions were separated by at least 48 hours. Progression to a lower body weight support level was determined by tolerance as described in Table 2.
*Body weight support, or delivered vertical force expressed as the percentage of body weight.
†Contact is defined as an instance of landing or changing direction on the surgical leg, eg. landing a hop, landing a jump, or cutting/pivoting on surgical side. The number of contacts listed is the actual number of contacts performed by the subject during that session.

Intervention

The jump training course, regardless of group assignment, involved 8 weeks of individual twice weekly sessions, each an hour long (Table 1). Each session began with verbal report of knee joint pain and muscle soreness and a stroke test to monitor joint effusion.[30] The participant then completed a 5-minute walking warm-up and a series of dynamic stretches to prepare the musculoskeletal and cardiovascular system for exercise. Jump training began immediately afterward. After completing the prescribed number of jump repetitions (contacts) as designated by group assignment, each participant completed a 5-minute walking cool-down and gentle stretching of the major muscle groups of the lower extremity, then reported knee joint and muscle pain again. A stroke test monitored post-training effusion. The training protocol for each group is detailed in Table 2. The task progression in both groups was similar to recently published neuromuscular training protocols.[31-34] Specific exercises and training repetition were adapted from those utilized in published ACL injury prevention programs.[33,34] Training repetition was tracked via contacts, defined as the number of times the involved leg hit the ground and/or generated a directional change (as in cutting). The JTBW group progressed from 80-100 contacts per session in the first week to 120-200 contacts per session in the 8th week.[35-37] In contrast, the JTBWS group had much higher repetition in the early phases of training. Repetition in both groups was maximized to patient tolerance within the limits set by each arm of the protocol as defined in Table 2.

For the first six weeks, the JTBWS group performed jump training in a custom BWS system described fully in previous work.[19,38] The system is designed to allow freedom of movement within a 1.5 x 3 x 4 m volume with a consistent vertical force, thereby providing movement and sport specificity with decreased impact loads.[19] Training was initiated at a BWS level of 30%, wherein a near-constant vertical force equal to 30% of the patient's body weight was exerted at the center of mass. The level of BWS was decreased every 2 weeks, from 30% to 20% to 10%, per tolerance to activity, with associated changes in repetition. The final two weeks of training were performed without BWS and were essentially the same as the final two weeks of training in the JTBW group in both exercises performed and repetition. All other training parameters, such as feedback, reinforcement, attentional focus, practice patterning, and introduction of sport-specificity (e.g. dribbling a basketball) progressed over time and similarly between groups, and have been detailed in previous work.[38]

In order to account for therapist belief or disbelief in treatment, cues and treatment progressions were scripted a priori. For example, all subjects had to correctly perform double leg jumping before progressing to single leg hop. Accordingly, they had to correctly perform a single leg squat before progressing to a single leg hop. All treatments were documented with a treatment log to ensure adequate procedural reliability. Four treatments for each subject were randomly selected for video-based fidelity analysis by an external physical therapist to ensure that treatments were equivalent between groups. Treatment logs and videos were reviewed with a standardized checklist documenting the number of steps in the protocol correctly completed per patient divided by the total number of steps. The mean percentage of steps performed correctly was compared between groups.

Randomization and Blinding

All protocols were prepared in advance and enclosed in sealed opaque envelopes. The envelopes were then sorted by an external statistician into a random sequence in blocks of 10 without stratification according to a computer generated random number sequence. Randomly sorted protocols were kept in a locked cabinet that the investigators were unable to access. A protocol was not assigned to a participant until they had signed informed consent documents, been determined as eligible for training and enrolled, and arrived for their first training session. An administrative assistant then retrieved the next envelope in the sequence and wrote the subject number on it prior to opening.

The testing clinician screened and enrolled eligible subjects. After enrollment, the testing clinician had no further contact with the participant until follow-up testing. The treating clinician instigated allocation procedures and administered the intervention. The testing clinician performed all follow-up testing, was blinded to group allocation, and remained blinded to group allocation through the analysis process.

Subjects were blinded to specific differences between treatments. Each subject was told that the two treatments differed in dose, but that both groups were expected to improve. Subjects were asked at the retention testing session whether they believed they were allocated to the control or experimental group, as well as whether they believed they performed a high or low dose of jump training.

Statistical Methods

A priori power calculations were performed to detect differences between groups in the co-contraction index and peak knee flexion with a two-sided test (α=0.5, β=0.8). The effect size was estimated from prior research demonstrating an effect of verbal instruction on both increasing knee flexion (d = 1.8) and decreasing co-contraction (d = 0.45) during single leg landing,[11] as well as from pilot training and testing. Seven subjects per group were needed to adequately test the hypotheses. Anticipating an attrition of 20% through training, we planned to enroll 20 subjects.

An intention-to-treat paradigm was utilized in the case of subjects lost to follow-up, with the last measurement carried forward. All variables of interest including kinematic, kinetic, muscle activation, patient-reported, and performance-based outcomes were checked for normality and outliers. Outliers were re-coded to a value of one unit beyond the next most extreme value.[39] All data were normally distributed after re-coding of outliers. Descriptive statistics were prepared for all variables of interest.

To address the question of whether jump training had an immediate effect on biomechanical, patient-reported, and performance-based outcome measures, comparisons were made between results from weeks 0, 4, and 8. There were no missing values in the kinematic and kinetic data, nor in patient-reported or SLHD outcomes data. Two-way ANOVAs by time and group were conducted for each patient-reported, kinematic, and kinetic variable of interest. Any significant effects were tested post-hoc with a Bonferroni correction. However, EMG data were corrupted with noise (e.g. large low frequency movement artifact) in 3 subjects at week 0, and in 2 subjects at week 4, requiring removal from the data set. As the loss occurred in the initial testing sessions, we were unable to perform statistical imputation procedures to complete the data set. In order to allow the remaining data from the subjects to contribute to the analysis, we took a modeling

Table 3. Descriptive characteristics of subjects by group. Continuous measures expressed as mean(SD).

Measure	Category	JTBW	JTBWS
Sex	Male	4	1
	Female	5	9
Age, years		21.1 (3.4)	24.9 (5.9)
BMI		28.0 (4.9) median=26.5	27.8 (10.8) median=26.4
Tegner Score		6.0 (1.6)	6.8 (1.8)
Injured Side	Dominant	5	3
	Non-Dominant	4	7
Time Since Surgery, months		17 (13.5)	18 (12.5)
Graft Type	Hamstring	3	3
	BPTB	4	7
	Cadaveric	2	0
Mechanism of Injury	Contact	6	5
	Non-Contact	3	5
Meniscus Injury	Injured	5	5
	Repaired	3	1
Postoperative PT	Range	0 – 6 months	2 – 9 months
	Mean	5 months	5 months

Abbreviations: JTBW, Jump Training with Normal Body Weight; JTBWS, Jump Training with Body Weight Support; BMI, Body Mass Index; PT, Physical Therapy approach. Each outcome was modeled with a general linear model with an interaction of time and group, which was compared with a mixed effects model with interaction of time and group with a random effect by subject. The models were compared using AIC and the model with the best fit was utilized.

To address the question of whether increased repetition improved the retention of motor skills, two-way ANOVAs by time (between weeks 8 and 16) and group were conducted for all variables of interest. No EMG data were lost in these testing sessions, and so were included in the two-way ANOVA testing. Post-hoc pairwise comparisons were made with a Bonferroni correction. Effect sizes were estimated using Cohen's *d*.

Instances of joint effusion greater than that with which each subject presented initially were recorded throughout training as a measure of tolerance to treatment. A two-proportion z-test compared the probability of developing effusion through the entire 8 weeks of training by group.

RESULTS

Thirty participants were screened for initial testing (Figure 1). Twenty-three were eligible to continue with training. Two declined treatment due to travel distance from the treatment and testing site; 1 declined treatment due to scheduling difficulties; and 1 declined treatment for personal reasons. In total, 19 participants (5 male, 14 female) were randomly assigned to either the JTBW or JTBWS treatment group (Table 3). Preferred activities and sports included soccer, basketball, football, skiing, snowboarding, Tai Kwon Do, Mixed Martial Arts fighting, and dance. Attrition was lower than expected, as one participant declined further treatment following the week 4 follow-up testing session due to time and scheduling constraints. No further exclusions were made following randomization.

Patient-reported functional outcomes, kinematic outcomes, and kinetic outcomes were available for all 19 subjects at all testing sessions. At initial testing, 16 subjects had EMG data available; at the 4 week testing session, 17 had EMG data; and all 19 subjects had EMG data at both the 8 and 16 week follow-up testing sessions.

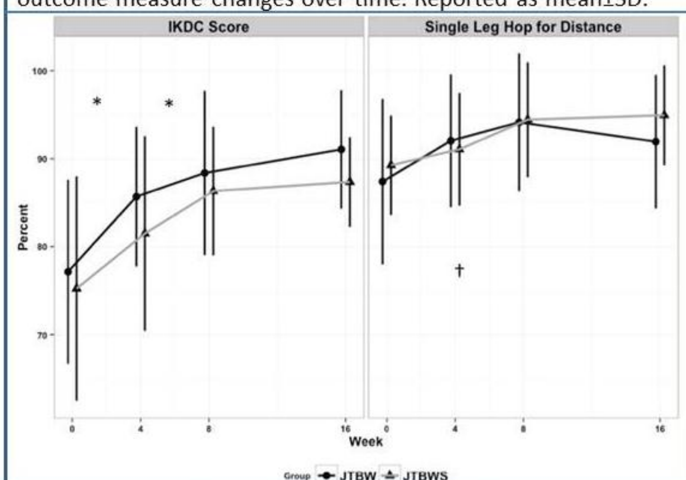
Of the 9 subjects allocated to the JTBW group, 5 believed they were part of the experimental group. Of the 9 subjects allocated to the JTBWS group that completed training, 7 believed they were part of the experimental group (*P* = 0.62). Subjects were also asked whether they believed they received a high or low dose of training. Of the 9 subjects in the JTBWS group, 7 believed they had received a high dose of training. Of the 9 subjects in the JTBW group, 7 believed they had received a high dose (*P* = 1.00).

Subjects in the JTBW group attended 91.7% of the treatment sessions, while subjects in the JTBWS group attended 91.9% of the treatment sessions; no subject missed more than 3 visits. There was no significant difference in the percentage of procedural checklist items performed with each group (*P* = 0.33; JTBW 96.1%, JTBWS 93.6%).

Primary Outcomes

With 8 weeks of jump training, both the JTBW and JTBWS groups saw statistically significant improvements in patient-reported function, hop distance performance, kinematics and kinetics, and neuromuscular behaviors during landing. There was no statistically significant effect of group; therefore, descriptive statistics, p-values, and effect sizes reported below are pooled between groups.

Figure 2. Patient-reported and performance-based functional outcome measure changes over time. Reported as mean±SD.



Abbreviations: IKDC, International Knee Documentation Committee Questionnaire; JTBW, Jump Training with Normal Body Weight; JTBWS, Jump Training with Body Weight Support

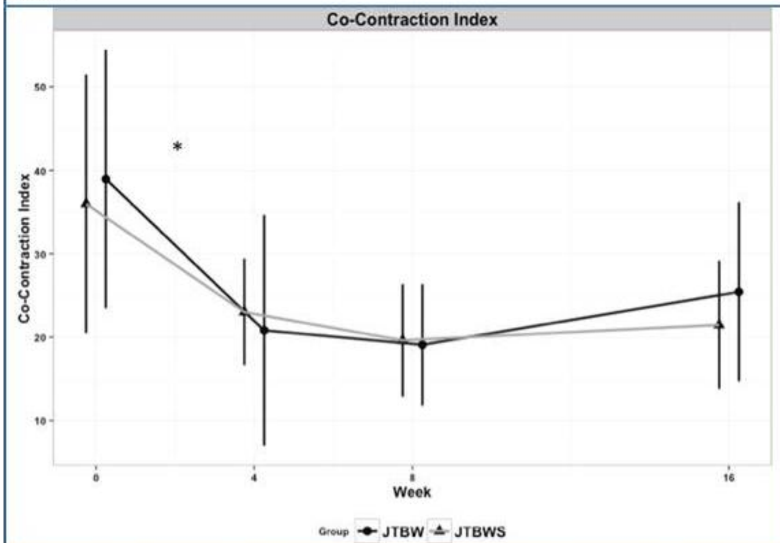
* Significant difference between consecutive tests *P*≤0.05

† Significant difference between week 0 and week 8 *P*≤0.05

Self-reported function as measured by the IKDC improved significantly from 76.1±11.5 at week 0 to 83.5±9.7 at week 4 (mean±SD; *P*=0.001; *d*=0.69; Figure 2). IKDC score improved further by week 8, to 87.3±8.2 (*P*=0.03; *d* = 0.43) for an overall training effect size of *d*=1.12. Participants' GRoC scores improved significantly from 4.9±0.9 at week 4 (GRoC score of 5 = "Quite a bit better") to 5.8±0.6 at week 8 (GRoC score of 6 = "A great deal better")(*P* = 0.004). Limb symmetry in the SLHD did not improve significantly from 88.4±7.5 at week 0 to week 4 (*P*=0.35), but did improve significantly to 94.3±7.0 by week 8 (*P*=0.02; *d*=0.82; Figure 2).

Peak hip flexion, knee flexion, and ankle dorsiflexion all increased significantly with training from week 0 to week 8 (*P* < 0.001; Table 4). Peak VGRF decreased significantly with training from week 0 to week 8 (*P* = 0.0004; Table 4). Peak hip moment also increased with training (*P* =0.0008; Table 4), though there was no significant effect of training on knee and ankle sagittal moments over the full 8 weeks.

Figure 3. Change in neuromuscular activation patterning over time.



Abbreviations: JTBW, Jump Training with Normal Body Weight; JTBWS, Jump Training with Body Weight Support
* Significant difference between consecutive tests *P*≤0.05

The co-contraction index during landing decreased from 37.2±15.0 to 18.58±6.1 over the training period (*d* = 1.26; Figure 3). The linear model without a random effect of subject was superior to the mixed effects model, with an AIC of 374.9 compared to 380.5, and was used for further analysis. There was a significant effect of time (β_{week} = -2.58, *P* = 0.0012; R^2 = 0.29, *p*=0.0003), but no significant effect of group. Maximal co-contraction decreased from 0.81±0.29 to 0.62±0.25 over the training period. Linear modeling without a random effect was again superior to a mixed effects model, but there were no significant effects of time or group (β_{week} = -0.02; *P* = 0.29; R^2 = 0.02).

Table 3. Peak Kinematic and kinetic changes over time by group. Measures are reported as mean(SD).

	Week	JTBW Group	JTBWS Group	P-values	
Kinematics					
Hip Flexion	0	48.1° (25.6°)	49.6° (14.4°)		
	4	72.2° (21.8°)	61.8° (12.3°)	0.0005	*
	8	73.8° (10.7°)	69.0° (14.8°)	0.26	†
	16	63.3° (25.7°)	68.6° (12.1°)	0.88	
Knee Flexion	0	59.0° (9.6°)	55.3° (11.5°)		
	4	72.6° (12.6°)	64.4° (8.9°)	0.0003	*
	8	76.8° (7.4°)	69.8° (9.4°)	0.08	†
	16	75.5° (9.0°)	69.5° (7.8°)	0.78	
Ankle Dorsiflexion	0	15.9° (7.2°)	14.5° (4.2°)		
	4	21.6° (7.4°)	17.9° (4.9°)	0.0002	*
	8	23.4° (5.9°)	21.2° (4.1°)	0.06	†
	16	22.4° (4.5°)	22.5° (5.6°)	0.90	
Kinetics					
Hip Flexion Moment, N·m/kg	0	2.62 (0.60)	2.29 (0.58)		
	4	3.68 (1.03)	2.87 (0.85)	<0.0001	*
	8	2.97 (0.51)	3.20 (0.64)	1.0	†
	16	3.00 (0.96)	3.01 (0.83)	0.71	
Knee Flexion Moment, N·m/kg	0	1.99 (0.42)	2.00 (0.41)		
	4	2.29 (0.47)	2.07 (0.54)	0.13	
	8	1.94 (0.35)	2.16 (0.44)	0.61	
	16	2.19 (0.56)	2.16 (0.43)	0.42	
Ankle Dorsiflexion Moment, N·m/kg	0	2.03 (0.41)	1.92 (0.24)		
	4	1.92 (0.33)	1.72 (0.21)	0.03	*
	8	1.93 (0.31)	1.80 (0.29)	1.0	
	16	1.82 (0.40)	1.77 (0.32)	0.51	
Vertical Ground Reaction Force	0	3.56 (0.39)	3.58 (0.49)		
	4	3.37 (0.39)	3.39 (0.31)	0.06	*
	8	3.01 (0.27)	3.26 (0.28)	0.002	†‡
	16	3.02 (0.77)	3.17 (0.45)	0.81	

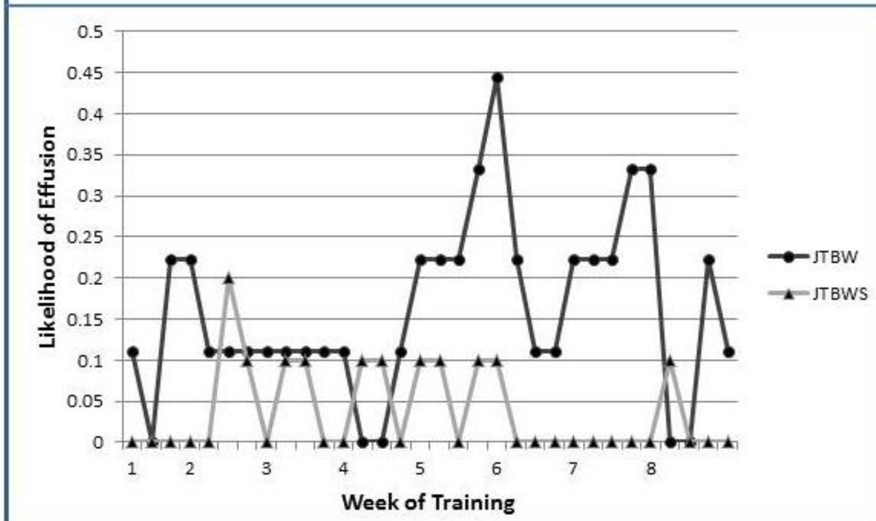
Vertical ground reaction force normalized and reported as a ratio of body weight
P-values reported between the week adjacent and the week above (0-4, 4-8, 8-16) and corrected for multiple comparisons between weeks 0, 4, and 8. No significant effect of group was found.
*Statistically significant difference between measure at week 0 and week 4.
†Statistically significant difference between measure at week 0 and week 8.
‡Statistically significant difference between measure at week 4 and week 8.

After the retention period following the training intervention, both the JTBW and JTBWS groups demonstrated no statistically significant changes compared to immediately following training in any of the primary variables of interest. There were no significant differences between groups or interactions between group and time; therefore, descriptive statistics, p-values, and effect sizes reported below are pooled between groups.

At the week 16 testing session, neither the IKDC score (89.1±6.1, P = 0.45; Figure 2), nor the GROC (5.9±1.1, P = 0.69) were different from that at the week 8 testing session. Kinematic and kinetic behaviors during landing were retained as well (*P* > 0.4; Table 4). Similarly, neuromuscular activation patterns were retained over the retention period. In both the JTBWS and JTBW groups, there was no statistically significant change in co-contraction index or maximal co-contraction between the week 8 and week 16 testing sessions (*P* > 0.1; Figure 3).

The stroke test for effusion was performed 32 times throughout training, before and after each session. For the JTBW group, the probability of effusion above that with which the subject presented at initial testing was 0.16. The probability of excessive effusion was significantly lower for the JTBWS group, at 0.05 (*P* < 0.0001; Figure 4).

Figure 4. Probability of presenting with effusion at each training session.



DISCUSSION

We hypothesized that jump training would improve function and decrease risk factors for osteoarthritis and re-injury. Additionally, we hypothesized that increased repetition with decreased intensity using BWS would improve retention of these effects. The results of the study support our first hypothesis, but do not support the second, in that both groups retained their improvement in all variables. Jump training, whether with or without BWS, improved patient reported function, hop performance, biomechanical measures, and neuromuscular behaviors in a patient group with previously limited outcomes following surgery.

The improvements with training are likely due to exposing the knee to activity specific stressors over an extended period. The current trial demonstrates continued improvement in patient-reported functional outcomes and in VGRF at 8 weeks compared with 4 weeks. Further, performance as measured by limb symmetry in the SLHD did not improve significantly at 4 weeks, but did improve by 8 weeks. The use of patient reported Global Rating of Change corroborates these subjective findings. All participants reported the condition of their knee was “quite a bit better” at the 4 week mark. By the conclusion of treatment at 8 weeks, the average patient report had improved even further to “A great deal better”. The GROC is a commonly used subjective instrument to quantify clinically meaningful improvements over time. [29] Treatment duration beyond 4 weeks was therefore required for the full training effect.

Brief instruction in landing technique has been shown to affect landing patterns and neuromuscular behaviors, though the retention of the effect is unknown.[11,13,26] In one study, instruction to soften landing resulted in increased hip and knee flexion from approximately 52° to 62° and 86° to 97° respectively in healthy athletes.[26] Following ACL reconstruction, the pattern of increased hip and knee flexion is similar while the values are fundamentally different. The results of the current study mirror the results of previous work, in which hip and knee flexion during landing increased from 46° to 66° and 56° to 77°, respectively.[11]

In a separate sample from the current clinical trial, we found a pre-instruction co-contraction index of 30.8±17.7, which improved to 23.7±15.4 with brief instruction to improve landing mechanics.[11] The subjects in the current study began at a higher average co-contraction index, concomitant with their lower than average knee flexion during landing. However, with extended training the subjects in the current trial decreased co-contraction to 18.58±6.1, beyond that found previously. Given that decreased co-contraction has been associated with decreased joint compression in landing, these changes in muscle activation could have a profound effect on joint compression during jumping tasks.[13]

The improvements in mechanical and neuromuscular risk factors for second injury and osteoarthritis are mirrored by improvements in function. Average IKDC score increased significantly from 76.1 to 87.3 with training. People with a history of knee problems have an average IKDC score of 56.6, whereas people with no history of knee problems have an average score of 83.5.[22] In this sample with mean age of 23 years, the average IKDC score improved from the 20th percentile of women 18-24 years old to the 40th percentile.

This study is the first to our knowledge to demonstrate retention of clinically meaningful mechanical and neuromuscular gains in post-ACL reconstruction population. Several studies in the neurological rehabilitation literature have demonstrated that retention of skills is dependent on repetition.[17,40-42] Studies investigating clinical practice patterns in neurological rehabilitation have found that in clinics patients were only exposed to low repetition training, even though improved skill development with increased repetition is well documented.[43] As a result, we are uncertain as to whether the JTBW group represents normal care or a best practice scenario. There is a dearth of quality evidence regarding the effects of jump training in a post-surgical population. The lack of difference in retention of kinematic, kinetic, and neuromuscular behavior, contrary to our hypothesis, may be thus explained by the larger-than-anticipated effect of jump training itself.

The subjects in the JTBW group did have a statistically higher probability of effusion with training, particularly as the intensity of training progressed in weeks 5-8. The current study is the first to our knowledge to examine effusion within an intervention study for patients with ACL reconstruction. While the improvements in impairment and functional level deficits were similar between groups, the higher repetition and lower intensity made possible by BWS may be clinically preferential to training with normal body weight.

While several studies have examined the effects of jump training on healthy athletes as part of ACL injury prevention programs,[33,44,45] relatively few have examined the effects of jump training on athletes following ACL reconstruction.[18,46,47] No other studies have examined the effects of training on mechanical and neuromuscular activation behaviors in a post-surgical population, yielding few comparators. The current study represents seminal data that helps explain how risk factors for re-injury and osteoarthritis can be manipulated in a lasting way through a retraining intervention in a post-surgical population.

A recently published study compared high and low intensity jump training 3 months following ACL reconstruction.[47] That study reported a 12-point change in the IKDC, similar to our 14-point change. It is notable that the average postoperative time frame of our subjects suggests that they had achieved more of a steady state of outcomes compared to those at only 3 months after surgery.[48] The changes made by the subjects in the current study are therefore less likely to be due to continued healing. Recent findings reported in abstract form compared functional changes with a jump training intervention post-ACL reconstruction via the IKDC and SLHD. That study demonstrated a similar trend to the results of the current study, but the effect was not significant.[46] In comparison, we demonstrate a profound effect on functional measures as well as risk factors for further problems. In that study, participants were not screened for need for training intervention prior to initiating training. Subjecting athletes who are already functioning optimally to extended plyometric training, therefore, may not be clinically efficient.

Only one study to our knowledge has compared the effects of higher (70 contacts per session, twice weekly) and lower (20 contacts per session, thrice weekly) repetition in jump training following ACL reconstruction.[18] Participants in the higher repetition group demonstrated a 20% greater improvement in the SLHD, while we show similar improvement in both groups. However, with 140 contacts per week, the high repetition group of that study completed approximately half of the contacts completed by the lower repetition group of the current study.[18]

The participants in the current trial differ from those of other recent studies primarily in their pre-training level of function. We utilized the initial session as a screen in order to avoid treating those athletes that did not require further intervention. Designating intervention to those patients with less than optimal outcomes represents a novel approach for intervention studies, but mirrors clinical reasoning for prescribing interventions. Because each participant self-identified as having less than optimal function, they may also have been more likely to adhere to the training schedule. Further, the participants in the current trial were, on average, 18 months post-surgical, whereas the participants in the other three trials have been, on average, within 3 to 6 months from surgery. People with poor outcomes at 1 year from surgery are unlikely to improve at 2 years from surgery.[48,49] The participants in the current trial, particularly given their heterogeneity in surgical procedure, surgeon, course of rehabilitation, age, and preferred activity, are therefore more likely to be representative of the population of athletes with poor long-term outcomes following ACL reconstruction.

Limitations of this trial include a small sample size and unequal gender distribution. The sample size was determined through an initial power analysis. A limited understanding of the potential of the selected participant group to improve may have led to an underestimation of the potential effect sizes within groups, and an overestimation of the effect between groups. This sample thus serves as a basis for a larger cross-sectional or multi-group study. Further research to explore the relative effects of training intensity and repetitions would further expand on these results.

There was also an unequal distribution of gender, with 5 males subjects in the JTBW group compared with 1 male subject in the JTBWS group, representing a failure of randomization on this variable. Previous investigations have demonstrated differences in landing performance and neuromuscular activation patterning between groups prior to initial injury and immediately following injury. Females are at higher risk of non-contact ACL injury, [25] and females with ACL-deficiency are less likely to be classified as copers following injury.[50] Gender may therefore play a role in group differences or lack thereof. The effect of gender in recovery following surgery remains unknown and untested in our trial.

The repetition level of the JTBW group in the current study was more than twice that delivered to the higher repetition group in other studies.[18] The JTBW group may have received higher-than-normal repetition. Indeed, there are no studies looking at actual repetition of plyometric activity in the course of normal rehabilitation following ACL reconstruction outside the academic environment. It is therefore possible that a lower repetition treatment would have yielded poorer retention; however, our object was to pursue best practice dosage parameters based on training tolerance.

Improved mechanical function and decreased co-contraction with training imply a decreased risk of osteoarthritis long-term, particularly in those athletes who retain decreased co-contraction in landing. Long-term prospective research is necessary to determine whether osteoarthritic and re-injury risk is in fact decreased in athletes who undergo extensive jump training. Utilization of biomarkers to evaluate cartilage degradation with activity may be a useful examination tool to contribute to the determination of change in osteoarthritic risk with intervention.[14] As patients with less-than-optimal outcomes following ACL reconstruction are unlikely to improve with time alone and long-term sequelae can be devastating, the results of the current trial indicate a positive step forward in intervention. A course of directed and highly cued jump training is a useful intervention strategy for those patients who do not attain their functional goals following ACL reconstruction.

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References

1. Mall NA, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med.* 2014;42(10):2363-2370.
2. Wilk KE, Macrina LC, Cain EL, Dugas JR, Andrews JR. Recent advances in the rehabilitation of anterior cruciate ligament injuries. *J Orthop Sports Phys Ther.* 2012;42(3):153-171.
3. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *Am J Sports Med.* 2010;38(11):2201-2210.
4. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.
5. Murphy L, Schwartz TA, Helmick CG, et al. Lifetime risk of symptomatic knee osteoarthritis. *Arthritis Rheum.* 2008;59(9):1207-1213.
6. Nyland J, Wera J, Klein S, Caborn DN. Lower extremity neuromuscular compensations during instrumented single leg hop testing 2-10 years following ACL reconstruction. *Knee.* 2014;21(6):1191-1197.

7. Ernst GP, Saliba E, Diduch DR, Hurwitz SR, Ball DW. Lower extremity compensations following anterior cruciate ligament reconstruction. *Phys Ther.* 2000;80(3):251-260.
8. Gauffin H, Tropp H. Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. *Am J Sports Med.* 1992;20(2):182-192.
9. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, O'Connor KM. The effects of single-leg landing technique on ACL loading. *J Biomech.* 2011;44(10):1845-1851.
10. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
11. Elias AR, Hammill CD, Mizner RL. Changes in quadriceps and hamstring cocontraction following landing instruction in patients with anterior cruciate ligament reconstruction. *J Orthop Sports Phys Ther.* 2015;45(4):273-280.
12. Vincent KR, Conrad BP, Fregly BJ, Vincent HK. The pathophysiology of osteoarthritis: a mechanical perspective on the knee joint. *PM R.* 2012;4(5 Suppl):S3-9.
13. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
14. Chmielewski TL, Trumble TN, Joseph AM, et al. Urinary CTX-II concentrations are elevated and associated with knee pain and function in subjects with ACL reconstruction. *Osteoarthritis Cartilage.* 2012;20(11):1294-1301.
15. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *J Orthop Sports Phys Ther.* 2006;36(5):308-319.
16. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2013;41(7):1549-1558.
17. Kerr AL, Cheng SY, Jones TA. Experience-dependent neural plasticity in the adult damaged brain. *Journal of communication disorders.* 2011;44(5):538-548.
18. Souissi S, Wong del P, Dellal A, Croisier JL, Ellouze Z, Chamari K. Improving Functional Performance and Muscle Power 4-to-6 Months After Anterior Cruciate Ligament Reconstruction. *J Sports Sci Med.* 2011;10(4):655-664.
19. Elias AR, Hammill CD, Mizner RL. The Effect of Body Weight Support on Kinetics and Kinematics of a Repetitive Plyometric Task. *J Appl Biomech.* 2015.
20. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. *J Orthop Sports Phys Ther.* 2006;36(6):385-402.

21. Hambly K, Griva K. IKDC or KOOS: which one captures symptoms and disabilities most important to patients who have undergone initial anterior cruciate ligament reconstruction? *Am J Sports Med.* 2010;38(7):1395-1404.
22. Anderson AF, Irrgang JJ, Kocher MS, Mann BJ, Harrast JJ, International Knee Documentation C. The International Knee Documentation Committee Subjective Knee Evaluation Form: normative data. *Am J Sports Med.* 2006;34(1):128-135.
23. Logerstedt D, Grindem H, Lynch A, et al. Single-legged hop tests as predictors of self-reported knee function after anterior cruciate ligament reconstruction: the Delaware-Oslo ACL cohort study. *Am J Sports Med.* 2012;40(10):2348-2356.
24. Reid A, Birmingham TB, Stratford PW, Alcock GK, Giffin JR. Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction. *Phys Ther.* 2007;87(3):337-349.
25. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc.* 2009;17(7):705-729.
26. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
27. Vos EJ, Harlaar J, van Ingen Schenau GJ. Electromechanical delay during knee extensor contractions. *Med Sci Sports Exerc.* 1991;23(10):1187-1193.
28. Rudolph KS, Axe MJ, Buchanan TS, Scholz JP, Snyder-Mackler L. Dynamic stability in the anterior cruciate ligament deficient knee. *Knee Surg Sports Traumatol Arthrosc.* 2001;9(2):62-71.
29. Kamper SJ, Maher CG, Mackay G. Global rating of change scales: a review of strengths and weaknesses and considerations for design. *J Man Manip Ther.* 2009;17(3):163-170.
30. Sturgill LP, Snyder-Mackler L, Manal TJ, Axe MJ. Interrater reliability of a clinical scale to assess knee joint effusion. *J Orthop Sports Phys Ther.* 2009;39(12):845-849.
31. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.
32. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
33. Lephart SM, Abt JP, Ferris CM, et al. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *Br J Sports Med.* 2005;39(12):932-938.
34. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *J Strength Cond Res.* 2012;26(8):2272-2292.

35. Chimera NJ, Swanik KA, Swanik CB, Straub SJ. Effects of Plyometric Training on Muscle-Activation Strategies and Performance in Female Athletes. *J Athl Train.* 2004;39(1):24-31.
36. Vaczi M, Tollar J, Meszler B, Juhasz I, Karsai I. Short-term high intensity plyometric training program improves strength, power and agility in male soccer players. *J Hum Kinet.* 2013;36:17-26.
37. Hewett TE, Stroupe AL, Nance TA, Noyes FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med.* 1996;24(6):765-773.
38. Elias AR, Kinney AE, Mizner RL. High repetition jump training coupled with body weight support in a patient with knee pain and prior history of anterior cruciate ligament reconstruction: A case report. *Int J Sports Phys Ther.* 2015;10(7).
39. Tabachnick BG, Fidell LS. *Computer-Assisted Research Design and Analysis.* Boston, MA: Allyn & Bacon; 2000.
40. Fine MS, Thoroughman KA. Motor adaptation to single force pulses: sensitive to direction but insensitive to within-movement pulse placement and magnitude. *J Neurophysiol.* 2006;96(2):710-720.
41. Combs SA, Dugan EL, Ozimek EN, Curtis AB. Bilateral coordination and gait symmetry after body-weight supported treadmill training for persons with chronic stroke. *Clin Biomech (Bristol, Avon).* 2013;28(4):448-453.
42. Mehrholz J, Pohl M, Elsner B. Treadmill training and body weight support for walking after stroke. *The Cochrane database of systematic reviews.* 2014;1:CD002840.
43. Lang CE, MacDonald JR, Gnip C. Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. *J Neurol Phys Ther.* 2007;31(1):3-10.
44. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sports Phys Ther.* 2013;43(11):777-792, A771-711.
45. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med.* 2013;41(1):203-215.
46. Kirby KW, Eskinazi-Budge S, Kelley S, Di Stasi SL, Hewett TE. The Effects of a 6-Week Neuromuscular Training Program on Fear and Knee Function Following Anterior Cruciate Ligament Reconstruction. *J Orthop Sports Phys Ther.* 2014;45(1):A152-A185.
47. Chmielewski TL. Low- vs High-Intensity Plyometric Exercise in Anterior Cruciate Ligament Reconstruction Rehabilitation. *Am J Sports Med.* 2015;IN PRESS.
48. Ardern CL, Taylor NF, Feller JA, Webster KE. Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2012;40(1):41-48.
49. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to the preinjury level of competitive sport after anterior cruciate ligament reconstruction surgery:

two-thirds of patients have not returned by 12 months after surgery. *Am J Sports Med.* 2011;39(3):538-543.
50. Hurd WJ, Axe MJ, Snyder-Mackler L. Influence of age, gender, and injury mechanism on the development of dynamic knee stability after acute ACL rupture. *J Orthop Sports Phys Ther.* 2008;38(2):36-41.

CONCLUSION

Extensive research has been conducted into the risk factors for injury and the rehabilitation from injury and surgery because of the frequency of ACL injury and the physical, emotional, and financial devastation it can cause. However, discrepancies in the literature continue to exist, particularly surrounding the role of coordination of the hamstrings and quadriceps in the neuromuscular control of the knee. Post-surgically, the role of co-contraction in performance, second injury risk, and the development of osteoarthritis has been poorly understood. The studies included in this dissertation represent a comprehensive study of the mechanical and neuromuscular impairments in weight acceptance that underlie the limitations to success following ACL reconstruction. A path toward improving functional recovery by treating impairments in landing is suggested and a novel training approach is tested. This dissertation thereby advances the science of rehabilitation to more effectively target mechanical and neuromuscular impairments that devastatingly contribute to the risk of re-injury and early onset osteoarthritis following ACL reconstruction.

Chapter 2: How does muscle recruitment patterning differ between athletes with a contact vs. a non-contact mechanism of injury?

Hypothesis 1: Individuals with a non-contact mechanism of injury will exhibit more co-contraction than individuals with a contact mechanism of injury.

People with a non-contact mechanism of injury tend to have higher co-contraction during a single leg landing as compared to people with a contact mechanism of injury, particularly in the non-surgical limb. In essence, the neuromuscular activation profile of a person with a contact injury mirrors that of the uninvolved limb of a person with a non-contact injury. Such results contrast with theoretical suppositions that co-contraction is a beneficial activation pattern. Rather, we found that co-contraction of the hamstrings with the quadriceps may not be an appropriate neuromuscular activation pattern. More importantly, these findings provide further support to the hypothesis that patients with a non-contact mechanism of injury may have an underlying impairment in their neuromuscular control, which has ramifications on major shortcomings in outcomes for second ACL injury risk and knee osteoarthritis.

Hypothesis 2: There will be coordination differences between limbs, with the operated limb exhibiting higher co-contraction.

Increased co-contraction was found in the involved limb of people with a contact injury. There is evidence that injury and reconstruction to the limb of a person with a non-contact injury increases co-contraction beyond that of a person with a contact injury. These results support findings demonstrating decreased co-contraction in people who can return to sport without surgical reconstruction of the injured ligament as compared to people who cannot.[1,2] Further, the results are consistent with findings that mechanism of injury is associated with the probability of a person being able to return to sport without surgical reconstruction.[3] The findings of this paper have important implications both for designing future studies that explore both the etiology of second ACL injury and knee osteoarthritis as well as for designing intervention programs to address neuromuscular impairments.

Chapter 3: What is the neuromuscular response to improved mechanics in landing?

Hypothesis 1: Landing performance of the operated limb will improve following instruction in landing technique, as measured by increased knee flexion angle and increased external knee flexion moments, and decreased peak vertical ground reaction forces compared to pre-instruction values.

Brief instruction improved landing performance in both kinematic and kinetic variables, supporting previous findings in both healthy and injured populations.[4,5] In order to consciously accomplish a soft landing, subjects increased knee and hip flexion, with concomitant reductions peak vertical ground reaction forces. Training of landing mechanics is recommended as a final step in return-to-sport rehabilitation in recently published practice guidelines for ACL reconstruction rehabilitation,[6,7] and our findings support such recommendations.

Hypothesis 2: Co-contraction of the hamstrings and quadriceps will decrease following instruction in landing technique.

The mechanical changes induced by instruction for a softer landing were associated with a decreased co-contraction of the quadriceps and hamstrings. The changes in co-contraction were primarily due to a significant decrease in hamstrings activity, with relative maintenance of quadriceps activation. The results of this and the previous study clarify the role of co-contraction of the hamstrings with the quadriceps in appropriate landing strategies as well as in the risk of second ACL injury and early-onset osteoarthritis.

Chapter 4: Can intensity of landing be modified while maintaining task-specificity?

Hypothesis 1: The body weight support system will provide consistent support throughout the hopping task.

We found that the custom body weight support system developed during this dissertation successfully provides a consistent level of body weight support. Support variability decreased as the amount of body weight support increased. At 20% body weight support, the vertical support varied by only 10% of the target load, over a vertical displacement of at least 13 cm, comparing favorably with over-treadmill systems.

Hypothesis 2: As body weight support increases, overall ground reaction forces and joint moments will progressively decrease, while kinematics will remain unchanged, thereby preserving the task specificity of training.

The application of body weight support to a repetitive plyometric task effectively mitigated impact loading, with decreased vertical ground reaction forces and joint moments. However, kinematic changes were negligible. The minimal kinematic change and a similar relative apportionment of load across the kinetic chain, regardless of body weight support level, indicated maintenance of task specificity. The BRIDGE allowed subjects in the following studies to complete sporting tasks with unrestricted joint motion while receiving a consistent unweighting force.

Chapter 5: Can the modifications to training dosage made possible by body weight support result in effective treatment?

Purpose: To report the outcomes of a patient with a previous history of ACL reconstruction treated with high repetition jump training coupled with body weight support as a primary intervention strategy. Changes in landing mechanics, psychological readiness for activity, and functional outcomes are detailed.

Body weight support was used to modify an evidence-based jump training protocol to mitigate the high intensity of jump training, allowing the patient in the case study to both increase training volume and target movement deficits in accordance with motor learning principles. The patient saw improved function, strength symmetry, and mechanical performance. Retention of all improvements after 8 weeks without training suggested that the new landing strategy had become a habitual pattern. The case report demonstrated that chronically dysfunctional movement patterns can be changed through direct intervention in the form of task-specific training, even with extensive time since the original injury and surgery.

Chapter 6: Are the mechanical and neuromuscular coordination effects of a high-repetition training intervention superior to those of a best-practice training intervention with relatively lower repetitions of practice?

Hypothesis 1: Jump training, whether low or high repetition, will improve functional, mechanical, and neuromuscular outcomes.

Jump training improved patient-reported function, performance, mechanical performance, and neuromuscular activation patterns in both intervention groups in our clinical trial. Changes continued to be made beyond the mid-point of training, suggesting that an extended period of training may be necessary to maximize the benefit of training. The group that trained without body weight support did tend to have a higher probability of effusion compared with the group training with body weight support. Thus, the use of body weight support with higher repetitions allowed potentially safer jump training with a decreased impact on the articular surfaces of the knee.

Hypothesis 2: High repetition training will result in improved retention of functional, mechanical, and neuromuscular gains.

Retention of all measures was seen in both groups, with no appreciable differences in function, performance, mechanics, or neuromuscular activation between the end of the training period and 8 weeks afterward.

SUMMARY

The series of studies included in this dissertation advance the understanding of the neuromuscular and mechanical deficits that coalesce to increase the risk of secondary problems following ACL reconstruction. Most egregiously, the majority of the people with ACL reconstruction will show radiographic evidence of knee osteoarthritis within 15 years of surgery.[8] Abnormal loading is exacerbated by a tendency toward co-contraction of the knee musculature, leading to even greater joint compression.[9] Co-contraction is demonstrated in the first two papers of this dissertation as having a detrimental effect on the knee joint, a paradigmatic shift from commonly accepted theories. Higher co-contraction is seen in people who have suffered a non-contact injury, and who are less likely to be able to dynamically stabilize their knee following ACL injury.[3] Further, co-contraction decreases with instruction to land with what is widely accepted as good technique. However, the effects of instruction on habitual movement patterns and muscle activation patterns have been poorly understood.

While jump training has been advocated for rehabilitative programs following ACL reconstruction, the effects of such programs on immediate and habitual movement patterns have not been well documented.[6,7,10,11] The ability to implement jump training programs with what is considered an effective dosage strategy for motor learning has itself been hampered by the intensity of jump landing.[12] Utilization of both good clinical assessment practices to titrate repetition to activity tolerance as well as body weight support to decrease intensity allowed increased repetition of jump landing in Chapter 6. Improvements in function, mechanics, and neuromuscular activation patterns were seen in both training groups, marking a substantive improvement to the outcomes of patients who previously had not had optimal outcomes. Most importantly, we demonstrated retention of functional, mechanical, and neuromuscular improvements, which to our knowledge has not been demonstrated in a post-surgical population. Indeed, very few studies have demonstrated retention of motor skills even with pre-injury risk reduction programs for healthy athletes.

By addressing the limitations to current practice in a novel fashion, this dissertation substantively improves upon clinical recommendations and thereby affects the quality of life for patients with ACL reconstruction. These studies should help guide clinical practice in the rehabilitation of athletes following ACL reconstruction. Jump training substantively improves outcomes on the impairment level, with improved weight acceptance and force attenuation, and on the functional level, with improved symmetry in functional performance tests as well as improve patient-reported function. Jump training delivered in higher repetition with reduced rate and amount of limb loading represents a treatment option that less chance of inducing an undesirable knee effusion. Given the devastating ramifications of ACL injury, effective and efficient treatment of the extensive neuromuscular and mechanical deficits seen following ACL reconstruction should be a clinical priority.

Further Research

The bilateral nature of the findings presented in Chapter 2 suggests a central, intrinsic source of the difference in neuromuscular control, present despite surgical correction of knee laxity. While consistent with findings demonstrating a decreased likelihood of pre-surgical coper status in those athletes with a non-contact mechanism of injury,[3] we are still unable to infer pre-injury co-contraction status from this study. Given that controversy still exists around the importance of co-contraction in primary injury risk reduction, prospective longitudinal studies utilizing EMG as part of injury risk screening are needed, though logistically difficult. Additionally, consideration of contact v. non-contact mechanism of injury is also warranted in further study into the long-term functional outcomes of ACL reconstruction, as well as the relative risks of re-injury and osteoarthritis.

Indeed, while musculoskeletal modeling has demonstrated a decrease in joint compression with decreased co-contraction,[5] the actual long-term impact of decreased co-contraction on joint health is unknown. The results presented in Chapter 3 suggest that instruction for appropriate landing mechanics results in increased knee flexion and decreased co-contraction of the hamstrings with the quadriceps, but the details of the modulations in moment and concomitant muscular activation around the hip and ankle remain controversial. Demand on the hip and ankle musculature has been surmised, but remains poorly understood, even while clinical recommendations are made to preferentially increase hip strength and control.[10,13] Determination of the effects of improved landing technique on the hip and ankle musculature is therefore of clinical importance.

In Chapter 4, we demonstrate maintenance of kinematic behaviors during a repetitive plyometric task with body weight support, and argue that this implies maintenance of task specificity. An examination of the response of physiological and muscular activation measures to body weight support is warranted in this case. Preferential changes in muscle recruitment may well be present, given the changes in internal moment. The different mechanisms of energy storage and return may also create a differential metabolic response to body weight support, which may further impact dosage and recovery considerations in exercise prescription.

The results of the randomized pragmatic trial in Chapter 6 demonstrate the power of jump training to affect functional and neuromuscular behaviors in a group with poor outcomes, and serve as a jumping-off point for future research. Firstly, the potential for body weight support to accentuate training earlier in the rehabilitative process must be examined. Other studies have demonstrated minor changes in functional and mechanical outcomes with jump training at 3 months following surgery,[14,15] but were hampered by comparatively small repetition of training due to the acuity of the surgery. Additionally, further research separating out low intensity/low repetition, low intensity/high repetition, and high intensity/low repetition will expand on the relationship between intensity and repetition in the learning of complex motor tasks. Most importantly, the improved mechanical function and decreased co-contraction found with training imply a decreased risk of osteoarthritis long-term. Prospective research is therefore necessary to determine whether the risk for osteoarthritis is in fact decreased in athletes who undergo extensive jump training. Utilization of serum and urine biomarkers to evaluate both articular cartilage synthesis and degradation with training activity may also contribute to the determination of change in osteoarthritic risk.

References

1. Rudolph KS, Eastlack ME, Axe MJ, Snyder-Mackler L. 1998 Basmajian Student Award Paper: Movement patterns after anterior cruciate ligament injury: a comparison of patients who compensate well for the injury and those who require operative stabilization. *J Electromyogr Kinesiol.* 1998;8(6):349-362.
2. Chmielewski TL, Rudolph KS, Snyder-Mackler L. Development of dynamic knee stability after acute ACL injury. *J Electromyogr Kinesiol.* 2002;12(4):267-274.
3. Hurd WJ, Axe MJ, Snyder-Mackler L. Influence of age, gender, and injury mechanism on the development of dynamic knee stability after acute ACL rupture. *J Orthop Sports Phys Ther.* 2008;38(2):36-41.
4. Mizner RL, Kawaguchi JK, Chmielewski TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther.* 2008;38(6):353-361.
5. Tsai LC, Powers CM. Increased hip and knee flexion during landing decreases tibiofemoral compressive forces in women who have undergone anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(2):423-429.
6. Adams D, Logerstedt DS, Hunter-Giordano A, Axe MJ, Snyder-Mackler L. Current concepts for anterior cruciate ligament reconstruction: a criterion-based rehabilitation progression. *J Orthop Sports Phys Ther.* 2012;42(7):601-614.
7. Hewett TE, Di Stasi SL, Myer GD. Current concepts for injury prevention in athletes after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2013;41(1):216-224.
8. Oiestad BE, Holm I, Aune AK, et al. Knee function and prevalence of knee osteoarthritis after anterior cruciate ligament reconstruction: a prospective study with 10 to 15 years of follow-up. *Am J Sports Med.* 2010;38(11):2201-2210.

9. Tsai LC, McLean S, Colletti PM, Powers CM. Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior cruciate ligament reconstruction. *J Orthop Res.* 2012;30(12):2007-2014.
10. Di Stasi S, Myer GD, Hewett TE. Neuromuscular training to target deficits associated with second anterior cruciate ligament injury. *J Orthop Sports Phys Ther.* 2013;43(11):777-792, A771-711.
11. Myer GD, Sugimoto D, Thomas S, Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *Am J Sports Med.* 2013;41(1):203-215.
12. Chmielewski TL, Myer GD, Kauffman D, Tillman SM. Plyometric exercise in the rehabilitation of athletes: physiological responses and clinical application. *J Orthop Sports Phys Ther.* 2006;36(5):308-319.
13. Myer GD, Ford KR, Brent JL, Hewett TE. An integrated approach to change the outcome part II: targeted neuromuscular training techniques to reduce identified ACL injury risk factors. *J Strength Cond Res.* 2012;26(8):2272-2292.
14. Souissi S, Wong del P, Dellal A, Croisier JL, Ellouze Z, Chamari K. Improving Functional Performance and Muscle Power 4-to-6 Months After Anterior Cruciate Ligament Reconstruction. *J Sports Sci Med.* 2011;10(4):655-664.
15. Kirby KW, Eskinazi-Budge S, Kelley S, Di Stasi SL, Hewett TE. The Effects of a 6-Week Neuromuscular Training Program on Fear and Knee Function Following Anterior Cruciate Ligament Reconstruction. *J Orthop Sports Phys Ther.* 2014;45(1):A152-A185.