ABSTRACT

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 subject with a previous history of anterior cruciate ligament (ACL) 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 ACL 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-designed body weight support system. The International Knee Documentation Committee Subjective Knee Form (IKDC) and the ACL-Return to Sport Index (ACL-RSI) were administered at the start and end of treatment as well as at follow-up testing.

Outcomes: The subject's IKDC and ACL-RSI scores increased with training from 68% and 43% to 90% and 84%, respectively, and were retained at follow-up testing. Peak knee and hip flexion angles during landing 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 – Case Report

Keywords: ACL-RSI, biomechanics, IKDC, plyometrics, 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. Initial outcomes following ACL reconstruction are quite good, with resolution of knee laxity and return to independent activities of daily living within three months. 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. Patients who have undergone ACL reconstruction often experience chronic impairment in mechanical performance of the operated limb. 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. 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. Additionally, people who have undergone ACL reconstruction frequently demonstrate high levels of fear of movement, or a lack of confidence in the knee.

Ardern et al and Chmielewski have both demonstrated that psychological impairments such as fear of movement and lack of confidence correlate with poor return to activity outcomes. Recent data 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 nearly half of patients who undergo ACL reconstruction develop early-onset osteoarthritis. Despite these shortcomings in long-term outcomes, there has been relatively little research performed exploring interventions designed to address chronic postsurgical psychological and mechanical impairments.

Plyometric or jump training has been recommended to improve mechanical deficits seen in the lower extremity following ACL reconstruction. However, the evidence supporting this recommendation has been from the literature on primary injury prevention in healthy athletes, and as such the specifics of exercise dosage may not translate to an injured population. Chmielewski 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. Recommendations for healthy athletes range from 20 contacts per session to 120 contacts per session. 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. Unfortunately, given the complexity and potential chronicity of the mechanical deficits involved postsurgically, low repetition training may not provide sufficient neuromuscular stimulus to allow modification of habitual movement patterns. While the literature regarding ways to optimize motor learning can be contradictory, it does seem that higher training volumes in the form of increased task repetition improves retention of that skill. 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 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. 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 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\(^4^2,4^3\) and for orthopedic rehabilitation\(^4^4-4^6\) 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.\(^4^7\) 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**

**Subject History and Systems Review**

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 who is a 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.\(^4^8\) 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 greater than 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 orthopedic 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

Isometric Strength 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 electromyographically 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,\(^{27,50}\) 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 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.

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

![Subjective & Psychological Questionnaire Scores](image)  
*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.
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. 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 had not attempted sport but had planned to return to their sport had scored a mean of 54.9%. Further, an ACL-RSI score at six months after surgery of 52.3% has been found to be a cut-off point using ROC analysis to discern between those athletes that eventually return to sport and those that do not (sensitivity = 0.97 specificity = 0.63).

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 strength values are below suggested side-to-side strength ratios typically advised for return to sport after ACL injury, which recommend 85% to 90% of the non-operated limb.

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.

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.

### 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, BWS allowed decreased intensity and higher repetition than the 20-120 contacts per session currently recommended for healthy athletes. 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. 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 var-

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

<table>
<thead>
<tr>
<th></th>
<th>Pre-Training</th>
<th>Post-Training†</th>
<th>Retention‡</th>
<th>Recommended§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadriceps</td>
<td>76.8%</td>
<td>86.4%</td>
<td>106.5%</td>
<td>90%</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>73.2%</td>
<td>71.1%</td>
<td>127.1%</td>
<td>90%</td>
</tr>
</tbody>
</table>

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

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

*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.

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

* 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.
ies by less than 10% through the 3-D movement of jumping up to 1.5 m. As such, the subject was able to perform high volume, sport-specific, jump landing training with decreased impact loads.

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. 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 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 train-

### Table 3. Jump training treatment progression

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

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/graying 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.
ing, 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 at re-testing, 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...
injured their ACL and undergone ACL reconstruction. Recent reviews by Ardern et al.\textsuperscript{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.\textsuperscript{41}

Following ACL reconstruction, many patients are released to sport based solely on the elapsed time since surgery.\textsuperscript{67} However, the intensity of the fear stimulus in returning to play may be psychologically traumatic.\textsuperscript{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, 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. Retention of these improvements after 8 weeks without training suggests that the new landing strategy had become a habitual pattern.

Chmielewski et al.\textsuperscript{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.\textsuperscript{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.\textsuperscript{41}

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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.42-45,70 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® (AlterG, Inc, Fremont, CA).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 report 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. In healthy humans performing upper extremity reaching task, 600 repetitions were required for learning. 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 kinematic information that is useful. 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 could be installed in a gym space 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.

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