Clinical Efficacy of Jump Training Augmented With Body Weight Support After ACL Reconstruction

A Randomized Controlled Trial

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Background: Limited knee flexion and increased muscle co-contraction during jump landing are believed to diminish outcomes after anterior cruciate ligament (ACL) reconstruction. The efficacy of jump training to improve patients’ mechanical and neuromuscular deficits is understudied.

Hypothesis: Jump training will improve functional, mechanical, and neuromuscular outcomes and higher repetition training augmented by body weight support will result in better retention of gains.

Study Design: Randomized controlled trial; Level of evidence, 1.

Methods: Thirty athletes (18 months after surgery) were screened, and 19 with mechanical deficits and limited clinical outcomes were enrolled in the trial. Testing included the International Knee Documentation Committee (IKDC) questionnaire, leg landing mechanics via motion analysis, knee joint effusion using a stroke test, and a surface electromyography–generated co-contraction index during a single-legged landing. Participants were randomly assigned to 1 of 2 groups: jump training with normal body weight (JTBW) and high-repetition jump training with body weight support (JTBWS). Knee effusion grading throughout training was used to assess joint tolerance. Changes in outcomes over time were analyzed with mixed-effects modeling. Immediate outcomes were compared with retention testing at 8 weeks after training by use of 2-way analyses of variance with effects of time and group.

Results: Significant effects of time were found during the training phase for all outcome measures, but no effects of group or sex were found. IKDC score (pooled; mean ± SD) increased from 76 ± 12 to 87 ± 8 (P < .001). Knee flexion during single-legged landing increased from 57° ± 11° to 73° ± 9° (P < .001). Average co-contraction index decreased from 37 ± 15 to 19 ± 6 (P < .001). All measures were retained over the retention period in both groups. The relative risk of knee effusion of the JTBW group versus the JTBWS group was 4.2 (95% CI, 2.25-7.71; P < .001).

Conclusion: Jump training mitigated some risk factors for second injury and osteoarthritis in patients after ACL reconstruction. Training made lasting improvements in physical function measures as well as mechanical and neuromuscular coordination deficits. Higher repetitions used with body weight support did not improve retention but substantially reduced risk for effusion.

Clinical Relevance: Jump training is an efficacious intervention for athletes with poor outcomes after ACL reconstruction, and training with body weight support lessens the risk for excessive joint stress during practice.

Registration: NCT02148172 (ClinicalTrials.gov identifier)

Keywords: biomechanics; clinical trial; jump training; knee

A growing body of evidence suggests that patients with anterior cruciate ligament (ACL) reconstruction commonly exhibit abnormal mechanical and neuromuscular behaviors in their operated knee during the tasks in which the knee is most frequently injured, such as landing from a jump.15,18,37 The operated knee can display large landing forces during weight acceptance, with decreased knee flexion and reduced knee flexion moments compared with the uninvolved limb.15 Musculoskeletal modeling has shown that these mechanical behaviors increase strain on the ACL during landing.26 The operated limb also responds to jump landing with increased co-contraction of the knee flexors and extensors compared with the uninvolved side and healthy peers.12,37,46 In vivo knee modeling suggests that co-contraction during landing is associated with
increased knee compressive forces compared with healthy limbs. Excessive loading is known to play a causative role in knee osteoarthritis. Thus, mechanical and neuromuscular limitations contribute to both reinjury and osteoarthritis risk.

Recent work has established that brief instruction in jump landing technique shows promise as a means to improve muscular force absorption and decrease co-contraction on a short-term basis after ACL reconstruction. Restoring the ability of the ACL-reconstructed limb to absorb landing forces muscularily could therefore decrease reinjury rates and mitigate arthritic changes. The effects of extended jump training after ACL reconstruction, however, are not known, which represents a gap in the current evidence base.

Important tenets of motor learning highlight the need for a high number of repetitions of a task to improve retention of a motor skill. Low repetition of jump training activity in healthy athletes with uninjured knees is frequently recommended due to high ground-reaction forces, and clinicians may further decrease repetition due to concern for the articular health of the already vulnerable joint. Such clinically reasonable but cautious restriction of repetition can be a barrier to effective dosing of jump training regimens and a reason for low effect sizes and poor retention of jump training interventions. However, only one study to date has compared the effects of varying doses of volume in plyometric training after ACL reconstruction; higher volume training resulted in greater improvements in functional performance measures, such as single-legged hop for distance, than lower volume training, although retention of improvements was not measured. Further, biomechanical and neuromuscular performance measures such as knee flexion, vertical ground-reaction forces (VGRFs), and co-contraction were not measured.

Managing clinically meaningful doses of jump training is challenging. For example, although increased repetition is allowed by decreased intensity, reducing intensity during jump landing is problematic. Current recommendations to lower the height of the jump still induce large and rapid limb loading when landing. Through use of body weight support (BWS), the intensity of jump landing tasks can be decreased with minimal effect on normal kinematic and kinetic behaviors, thereby allowing increased repetition of training.

The purpose of this study is therefore 2-fold: (1) to examine the effect of a 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, regardless of low- or high-repetition dosage, will improve outcomes but that higher repetition training will result in improved retention of functional, mechanical, and neuromuscular gains compared with a best practice but lower repetition training intervention. Further, we posit that the group trained under BWS 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 comparative value of 2 programs, a high-repetition jump training program with BWS and a best practice plyometric training program, in a population of athletes with suboptimal outcomes after ACL reconstruction, through use of patient-reported function, performance outcomes, and biomechanical measures. Participants underwent an initial screening evaluation to determine appropriateness for intervention after ACL reconstruction. Individual participants who had functional and biomechanical deficits were considered in need of training and were randomly assigned to 1 of 2 individual 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’s institutional 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 flyers posted on and off the University of Montana campus, by community advertising, and by word-of-mouth from local physical therapists and orthopaedic surgeons. Participants were eligible for screening if they were between 6 and 48 months after ACL reconstruction, were between the ages 18 and 50 years old, had a minimum of 6 months of deterioration of functional performance and biomechanical measures, and were considered in need of training. Individuals who were unwilling to start training, had musculoskeletal limitations that they hoped to address with training, or had a high-risk lifestyle for reinjury were excluded. Individuals with an osteoarthritis diagnosis were also excluded.

One or more of the authors has declared the following potential conflict of interest or source of funding: Funding was provided by grants from the Orthopaedic Section of the American Physical Therapy Association and the Foundation for Physical Therapy. R.L.M. is recognized as a coinventor of intellectual property that has been submitted for patent protection by the University of Montana’s Office of Technology Transfer regarding a device used to deliver body weight support as part of the intervention piece of the trial described in the manuscript. That patent application is currently under review.
of 12 and 35 years, had been cleared for sports participation by their surgeon, and participated in recreational or competitive sports at a Tegner Activity Scale level higher than 4.

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.

Participants met eligibility criteria for randomization into treatment groups based on the International Knee Documentation Committee (IKDC) Subjective Knee Form questionnaire, single-legged hop for distance (SLHD) limb symmetry, or peak knee moment during single-legged landing. Eligible scores were defined by previously published return to sport standards for IKDC and SLHD limb symmetry, and by peak knee moment falling further than 1 SD below the mean, as determined by a database of athletes meeting the same inclusion and exclusion criteria previously tested. Effectively, scores lower than 75 on the IKDC, a limb symmetry index lower than 75% in a single-legged hop for distance test, or a peak knee moment less than 2.3 body weights and lower than 80% of the nonsurgical side during a single-legged landing task identified participants who would benefit from intervention.

Participants meeting 1 or more of the eligibility criteria were offered placement in the clinical trial. Upon acceptance, each participant was randomly allocated to 1 of 2 intervention groups as detailed in the CONSORT (Consolidated Standards of Reporting Trials) flow diagram (Figure 1).

Testing procedures occurred in the following order: administration of the IKDC; 5-minute treadmill walking warm-up; placement of electromyography (EMG) electrodes; maximal voluntary isometric contraction (MVIC) and strength testing; placement of retroreflective markers; static standing patient calibration; completion of the SLHD test; and biomechanical analysis of hopping tasks as detailed below.

Figure 1. CONSORT (Consolidated Standards of Reporting Trials) diagram. EMG, electromyography; JTBW, jump training with normal body weight; JTBWS, jump training with body weight support.
Setting

All testing and training took place in the Movement Science Laboratory on the University of Montana campus. Participants allocated to the JTBW condition completed their training using 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 used knee-specific, patient-reported functional outcome measure documenting symptoms as well as participation in daily functional and sports activities, and its use is consistent with clinical practice guidelines. The SLHD is a commonly used, reliable, and valid performance-based outcome measure. Testing and limb symmetry expression were completed in accordance with previously published methods.40

**Biomechanical Outcomes.** EMG, kinematic, and kinetic data were obtained during the landing phase of a single-legged landing task as previously described.12 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.

**Electromyographic Testing.** In preparation for EMG analysis of the single-legged landing task, vastus lateralis and biceps femoris MVC testing was performed with the patient in a seated position using a Kin-Com 125AP dynamometer (Chattanooga Group) in accordance with previously published methods.12,31 Muscle activation levels recorded with surface EMG (sEMG) during the MVIC trial with the greatest torque produced were used for sEMG normalization during analysis of the single-legged landing task.

The sEMG signals were processed as previously described11 and then normalized to the peak sEMG signal obtained during the peak MVIC trial. Normalized signal was used for analysis of co-contraction during the single-legged landing task. The wire from the participant to the recording system was managed to avoid restricting the participant in any way during hop tasks.

Instantaneous co-contraction was defined as the weighted ratio between hamstring and quadriceps activation, and the co-contraction index (CoI) was the integral of that function across the weight acceptance phase of landing as previously described.12,31 Both the CoI and maximal instantaneous co-contraction were used as measures of muscle activation pattern, with the CoI designated as a primary outcome of motor learning.

**Biomechanical Testing.** Kinematic and kinetic data were obtained during landing tasks and processed via previously published methods.12 Joint angles and moments were time normalized to 100 increments from 100 milliseconds before initial contact on the force plate to peak knee flexion during landing (the weight acceptance phase) to enable the calculation of an ensemble average across trials for each participant.

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. Waiting 8 weeks exceeds the retention testing period of several prior works of jump training in healthy athletes.28,50 Further, 8 weeks provides a reasonable period to represent the length of a competitive season of sport. The definition of the weight acceptance phase during landing was modified in the trained state to end at either peak knee flexion or when the VGRF returned to 1 body weight after peak VGRF, whichever came first: in the trained state, participants tended to continue to bend their knees after full weight acceptance, artificially extending the landing phase. This new definition allowed comparison of integrated EMG between trials.

**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.23

Intervention

The jump training intervention, regardless of group assignment, involved 8 weeks of individual twice-weekly sessions, each an hour long (Table 1). Each session began and ended with verbal report of knee joint pain and muscle soreness and a stroke test to monitor joint effusion. Results influenced task and repetition progression as described in Table 1. Repetition in both groups was maximized to patient tolerance within the limits set by each arm of the protocol as described in Table 2. 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 eighth week.6,21,47 In contrast, the JTBW group had much a higher number of repetitions in the early phases of training, according to the decreased intensity of the task from the BWS system. The task progression in both groups was similar to that described in recently published neuromuscular training protocols.1,20,27,33 Specific exercises and training repetitions were adapted from those used in published ACL injury prevention programs.27,33

For the first 6 weeks, the JTBW group performed jump training in a custom BWS system described fully in previous work.13,14 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 by 10% every 2 weeks per tolerance to activity, with associated changes in repetition according to the kinetic effects of BWS on the knee moment in landing.13 The final 2 weeks of training were performed without BWS and were essentially the same as the final 2 weeks of training in the JTBW group in terms of both exercises performed and number of
repetitions. 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, as detailed in previous work.14 Both groups trained in the highest intensity landing tasks they were able to perform correctly at that time. The reduced limb loads with the BWS system allowed participants allocated to the JTBWS group to perform single-legged landing tasks correctly much earlier than those in the JTBW group.

To account for therapist belief or disbelief in treatment, cues and treatment progressions were scripted a priori. For example, all participants had to correctly perform a single-leg squat and double-leg jumping before progressing to single-legged hop. All treatments were documented with a treatment log to ensure procedural reliability. Four treatments for each participant were randomly selected for video-based fidelity analysis by an external physical therapist to ensure that the training parameters were equivalent between participants and 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. An administrative assistant assigned a protocol to a participant once the participant had signed informed consent documents, been determined as eligible for training and enrolled, and arrived for the first training session.

The testing clinician screened and enrolled eligible participants. After enrollment, the testing clinician had no further contact with the participant until scheduled testing and was blinded to group allocation through the analysis process. The treating clinician instigated allocation procedures and administered the intervention.

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**TABLE 1**

<table>
<thead>
<tr>
<th>Treatment Component</th>
<th>Specific Task</th>
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</thead>
<tbody>
<tr>
<td>Joint reaction check (for previous treatment)</td>
<td>Knee pain rating on 0-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion</td>
</tr>
<tr>
<td>Warm-up</td>
<td>5-min treadmill walking (3-3.5 mph) High knee running Heel-to-gluteal running High kick walking Hip wrap walking with heel raise Walking lunges</td>
</tr>
<tr>
<td>Jump training</td>
<td>Contacts—JTBW Contacts—JTBWS</td>
</tr>
<tr>
<td>Week 1 and 2</td>
<td>80-100 200-350</td>
</tr>
<tr>
<td>Week 3 and 4</td>
<td>80-160 250-500</td>
</tr>
<tr>
<td>Week 5 and 6</td>
<td>120-200 200-350</td>
</tr>
<tr>
<td>Week 7 and 8</td>
<td>120-200</td>
</tr>
<tr>
<td>Cool-down</td>
<td>5-min treadmill walking (3-3.5 mph) Quadriceps stretch (30 s) Hamstrings stretch (30 s) Calf stretch (30 s) Hip abductor stretch (30 s)</td>
</tr>
<tr>
<td>Joint reaction check (for current treatment)</td>
<td>Knee pain rating on 0-10 VAS Report of muscle soreness and fatigue Stroke test for joint effusion</td>
</tr>
</tbody>
</table>

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*aAdapted from an intervention previously described by Elias et al.14 Total treatment time was 1 hour per session. JTBW, jump training with normal body weight; JTBWS, jump training with body weight support; VAS, visual analog scale.

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

*cContact is defined as an instance of landing or changing direction on the surgical leg: e.g., landing a hop, landing a jump, or cutting/pivoting on surgical side. The number of contacts listed is the range of actual contacts performed by participants during that session.

*dIf knee pain increased more than 2 levels during treatment, the next treatment did not progress in repetition or intensity. Muscle soreness and fatigue were noted for comparison with the next pretreatment check. If the stroke test was graded more than 1 level above the pretreatment grade, the next treatment did not progress in repetition or intensity.
Patients were blinded to specific differences between treatments. Each patient was told that the 2 treatments differed in dose but that both groups were expected to improve. Patients 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 2-sided test (α = .5, β = .8). The effect size (Cohen’s $d$) 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-legged landing, as well as from pilot training and testing. Seven patients per group were needed to adequately test the hypotheses. Anticipating an attrition of 20% through retention of motor skills, we conducted 2-way analyses of variance by time (between weeks 0, 4, and 8) and group for sex with interaction of time and group with a random effect by patient. The models were compared through use of the Akaike information criterion (AIC) as a measure of fit, and the model with the best fit was used.

To address whether increased repetition improved the retention of motor skills, we conducted 2-way analyses of variance by time (between weeks 8 and 16) and group for all variables of interest. Post hoc pairwise comparisons were made with a Bonferroni correction. Effect sizes were estimated by use of Cohen’s $d$.

Knee joint effusion was graded at each testing session as a measure of tolerance to treatment. Each instance of joint effusion graded higher than that at the initial testing session was counted, and a 95% confidence interval of the relative risk of effusion between the 2 groups was developed.

EMG data were corrupted with noise (eg, large, low-frequency movement artifact) in 3 patients at week 0 and in 2 patients 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. The groups were also dissimilar by sex (Table 3). Previous investigations have found that women are at higher risk of noncontact ACL injury, and women with ACL deficiency are less likely to be classified as copers after injury. To allow all data to contribute to the analysis and to account for potential sex differences, we took a modeling approach to address whether jump training had an immediate effect on biomechanical, patient-reported, and performance-based outcome measures between weeks 0, 4, and 8. Each outcome was modeled with a general linear model accounting for sex with an interaction of time and group as well as a mixed-effects model accounting for sex with interaction of time and group with a random effect by patient. The models were compared through use of the Akaike information criterion (AIC) as a measure of fit, and the model with the best fit was used.

To address whether increased repetition improved the retention of motor skills, we conducted 2-way analyses of variance by time (between weeks 0 and 4) and group for whether they believed the control or experimental group as well as whether they believed they performed a high or low dose of jump training.

### TABLE 2

Jump Training Treatment Progression Protocol

<table>
<thead>
<tr>
<th>Phase</th>
<th>Contacts</th>
<th>Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1</td>
<td>Technique</td>
<td>80-100 Vertical jumps, lateral jumps, broad jumps, spinning jumps,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>split jumps, tuck jumps, stationary bounding</td>
</tr>
<tr>
<td>Week 2</td>
<td></td>
<td>Above, plus triple jumps, vertical hops, lateral hops</td>
</tr>
<tr>
<td>Week 3</td>
<td></td>
<td>80-160 Above, plus triple jumps, vertical hops, lateral hops</td>
</tr>
<tr>
<td>Week 4</td>
<td></td>
<td>120-200 Above, plus combination jumps, lateral cutting, triple</td>
</tr>
<tr>
<td>Week 5</td>
<td></td>
<td>broad hops, box hops</td>
</tr>
<tr>
<td>Week 6</td>
<td></td>
<td>120-200 Above, plus lateral box hops, agility drills</td>
</tr>
<tr>
<td>Week 7</td>
<td></td>
<td>120-200 Above, plus lateral box hops, agility drills</td>
</tr>
<tr>
<td>Week 8</td>
<td></td>
<td>120-200 Above, plus lateral box hops, agility drills</td>
</tr>
</tbody>
</table>

*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 1.

*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 range of actual contacts performed by participants during that session.

*Body weight support is defined as the delivered vertical force expressed as the percentage of body weight.
RESULTS

Thirty participants were screened for initial testing (Figure 1). Twenty-three were eligible to continue with training. Four participants declined treatment. In total, 19 participants (5 men, 14 women) were randomly assigned to either the JTBW or JTBWS treatment group (Table 3). Of those, 9 participants met 2 of the 4 eligibility criteria, 8 participants met 3 of the 4 criteria, and 2 participants met all 4 criteria. Preferred activities and sports included soccer, basketball, football, skiing, snowboarding, taekwondo, mixed martial arts fighting, and dance. One participant declined further treatment after the week 4 follow-up testing session due to time constraints. No further exclusions were made after randomization.

Of the 9 participants allocated to the JTBW group, 5 believed they were part of the experimental group, compared with 7 of the 9 participants allocated to the JTBWS group (Table 3). Of those, 9 participants met 2 of the 4 eligibility criteria, 8 participants met 3 of the 4 criteria, and 2 participants met all 4 criteria. Preferred activities and sports included soccer, basketball, football, skiing, snowboarding, mixed martial arts fighting, and dance. One participant declined further treatment after the week 4 follow-up testing session due to time constraints. No further exclusions were made after randomization.

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Primary Outcomes

With 8 weeks of jump training, both the JTBW and JTBWS groups improved in patient-reported function, hop distance performance, kinematics and kinetics, and neuromuscular behaviors during landing. No statistically significant effect of group was found on any measure; therefore, reported descriptive statistics and effect sizes are pooled between groups. Mixed-effects models were superior to linear models based on the AIC for all outcomes and were used for analysis.

Self-reported function as measured by the IKDC improved from 76.1 ± 11.5 at week 0 to 87.3 ± 8.2 at week 8 (mean ± SD; d = 1.12) (Figure 2). Limb symmetry in the SLHD improved from 88.4% ± 7.5% at week 0 to 94.3% ± 7.0% by week 8 (d = 0.82) (Figure 2). The results showed a significant effect of time for both IKDC and SLHD (βweek = 1.40, P < .0001; βweek = 0.74, P < .002, respectively) but no significant effect of group or sex. 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 = .004).

Peak hip flexion, knee flexion, and ankle dorsiflexion all increased and peak VGRF decreased with training from week 0 to week 8 (P < .0001) (Table 4). Peak hip moment also increased with training (P = .002), although we found no effect of training on knee and ankle sagittal moments over the full 8 weeks (P > .1). In all biomechanical measures, no significant effect of group or sex was found (P > .1).

The co-contraction index during landing decreased from 37.2 ± 15.0 to 18.6 ± 6.1 over the training period (d = 1.26) (Figure 3). Again, the results showed a significant effect of time (βweek = −2.17, P < .0001) but, again, no significant effect of sex or group.

After the retention period following the training intervention, both the JTBW and JTBWS groups demonstrated no statistically significant changes compared with immediately

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TABLE 3
Descriptive Characteristics of Patients by Groupa

<table>
<thead>
<tr>
<th>Measure Category</th>
<th>JTBW</th>
<th>JTBWS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex, n</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Age, years</td>
<td>21.1 (3.4)</td>
<td>24.9 (5.9)</td>
</tr>
<tr>
<td>Body mass index</td>
<td>28.0 (4.9)</td>
<td>27.8 (10.8)</td>
</tr>
<tr>
<td>Tegner score</td>
<td>6.0 (1.6)</td>
<td>6.8 (1.8)</td>
</tr>
<tr>
<td>Injured side, n</td>
<td>17 (13.5)</td>
<td>18 (12.5)</td>
</tr>
<tr>
<td>Graft type, n</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Mechanism of injury, n</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Meniscal injury, n</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Postoperative physical therapy, mo</td>
<td>0-6</td>
<td>2-9</td>
</tr>
</tbody>
</table>

aContinuous measures expressed as mean (SD). JTBW, jump training with normal body weight; JTBWS, jump training with body weight support.
after training in any of the primary variables of interest. Again, no significant differences were found 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, $P = .45$) (Figure 2) nor the GROC (5.9 ± 1.1, $P = .69$) was different from that at the week 8 testing session. Kinematic and kinetic behaviors during landing were retained as well ($P > .4$) (see Table 4). Similarly, neuromuscular activation patterns were retained over the retention period. In both the JTBWS and JTBW groups, no statistically significant change was found in co-contraction index or maximal co-contraction between the week 8 and week 16 testing sessions ($P > .1$) (see Figure 3).

The stroke test for effusion was scheduled to be performed 32 times for each participant throughout the intervention, before and after each training session. The relative risk of knee effusion of the JTBW group to the JTBWS group was 4.2 (95% CI, 2.25-7.71; probability of effusion: JTBW = 0.16; JTBWS = 0.04) (Figure 4).

**Table 4**

<table>
<thead>
<tr>
<th>Kinematic parameters</th>
<th>Group</th>
<th>Week 0</th>
<th>Week 4</th>
<th>Week 8</th>
<th>Week 16</th>
<th>Effect of Time</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip flexion angle, deg</td>
<td>JTBW</td>
<td>48.1 (25.6)</td>
<td>72.2 (21.8)</td>
<td>73.8 (10.7)</td>
<td>63.3 (25.7)</td>
<td>1.32</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>49.6 (14.4)</td>
<td>61.8 (12.3)</td>
<td>69.0 (14.8)</td>
<td>68.6 (14.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion angle, deg</td>
<td>JTBW</td>
<td>59.0 (9.6)</td>
<td>72.6 (12.6)</td>
<td>76.8 (7.4)</td>
<td>75.5 (9.0)</td>
<td>1.64</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>55.3 (11.5)</td>
<td>64.4 (8.9)</td>
<td>68.9 (8.4)</td>
<td>69.5 (7.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle flexion angle, deg</td>
<td>JTBW</td>
<td>15.9 (7.2)</td>
<td>21.6 (7.4)</td>
<td>23.4 (5.9)</td>
<td>22.4 (4.5)</td>
<td>1.33</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>14.5 (4.2)</td>
<td>17.9 (4.9)</td>
<td>21.2 (4.1)</td>
<td>22.5 (5.6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kinetic parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip flexion moment, N·m/kg</td>
<td>JTBW</td>
<td>2.6 (0.6)</td>
<td>3.7 (1.0)</td>
<td>3.0 (0.5)</td>
<td>3.0 (1.0)</td>
<td>1.11</td>
<td>.002</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>2.3 (0.6)</td>
<td>2.9 (0.9)</td>
<td>3.2 (0.6)</td>
<td>3.0 (0.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knee flexion moment, N·m/kg</td>
<td>JTBW</td>
<td>2.0 (0.4)</td>
<td>2.3 (0.5)</td>
<td>1.9 (0.4)</td>
<td>2.2 (0.6)</td>
<td>0.16</td>
<td>.46</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>2.0 (0.5)</td>
<td>2.1 (0.5)</td>
<td>2.2 (0.4)</td>
<td>2.2 (0.4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ankle dorsiflexion moment, N·m/kg</td>
<td>JTBW</td>
<td>2.0 (0.4)</td>
<td>1.9 (0.3)</td>
<td>1.9 (0.3)</td>
<td>1.8 (0.4)</td>
<td>0.33</td>
<td>.14</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>1.9 (0.2)</td>
<td>1.7 (0.2)</td>
<td>1.8 (0.3)</td>
<td>1.8 (0.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical ground-reaction force</td>
<td>JTBW</td>
<td>3.6 (0.4)</td>
<td>3.4 (0.4)</td>
<td>3.0 (0.3)</td>
<td>3.0 (0.8)</td>
<td>1.17</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td></td>
<td>JTBWS</td>
<td>3.6 (0.5)</td>
<td>3.4 (0.3)</td>
<td>3.3 (0.3)</td>
<td>3.2 (0.5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

aValues are reported as mean (SD). Effects of time are reported as Cohen’s $d$ from week 0 to week 8 and pooled between groups. Vertical ground-reaction force and joint external moments were normalized and reported as ratio of body weight. JTBW, jump training with normal body weight; JTBWS, jump training with body weight support. 

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Figure 2. Patient-reported and performance-based functional outcome measure changes over time. Reported as mean ± SD. 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, $P \leq .05$. †Significant difference between week 0 and week 8, $P \leq .05$.

Figure 3. Change in neuromuscular activation patterning over time. Reported as mean ± SD. JTBW, jump training with normal body weight; JTBWS, jump training with body weight support. *Significant difference between consecutive tests, $P \leq .05$. †Significant difference between week 0 and week 8, $P \leq .05$. 

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IKDC scores (76.1\% effusion in those athletes training with BWS. It is notable that the average postoperative time-change.7 It is conceivable that a lower repetition
suggestion that they had achieved more of a steady state of outcomes compared with those at only 3 months after surgery.4 Patients’ clinical outcomes generally remain stable with the passage of time following 1 year from surgery.4,34 Patients’ initial testing therefore served as their own comparative standard for improvements made in the current trial. Interestingly, while gains in self-reported function and performance were largest in the first 4 weeks of training, gains continued through 8 weeks. To see a statistically significant change in performance as measured by SLHD, a full 8 weeks of training was required.

Improvements in physical function are mirrored by improvements in mechanical and neuromuscular risk factors during landing, similar to those seen with brief, one-time instruction in landing technique.12,31,46 However, unlike self-reported function and performance, the kinetic, kinematic, and co-contraction measures improved most drastically in the first 4 weeks of training and then saw no statistically significant change. This suggests that training for an additional 4 weeks with improved mechanical and neuromuscular behaviors allowed increased function and performance.

The participants in the current study began training at a higher average co-contraction index (week 0, mean ± SD: 38.1 ± 16.5) than seen previously in our laboratory in athletes without instruction (30.9 ± 17.7). Higher co-contraction and decreased knee sagittal moment are expected given our inclusion criteria to target athletes who needed training intervention. However, with training, the patients in the current trial decreased co-contraction (week 8: 18.5 ± 6.3) beyond that found previously in athletes who were given 5 minutes of landing instruction (23.74 ± 15.39). Such enhanced changes and retention after training suggest that greater improvement in mechanics and neuromuscular outcomes can be achieved with repeated training sessions over time as opposed to a single, brief period of instruction.

Several studies in the neurological rehabilitation literature have demonstrated that retention of skills is dependent on repetition.10,16,24,30 No study has examined the effect of repetition on retention with this intervention, and only one study to our knowledge has compared the immediate effects of higher (70 contacts per session, twice weekly) and lower (20 contacts per session, thrice weekly) repetition in jump training after ACL reconstruction.42 Participants in the higher repetition group in that previous study demonstrated a 20\% greater improvement in the SLHD than the lower repetition group, and in the current study we show similar improvement in both groups. However, the repetition level of the JTBW group in the current study was more than twice that delivered to the higher repetition group in the previous study.42 It is possible that a threshold level of repetition exists, such that repetition above that level is superfluous for immediate gains; however, additional study is necessary to determine the ideal level of repetition required for retention of gains. In the current study, the level of repetition in the JTBW group may have been at or above that ideal level, potentially explaining the lack of difference in retention of kinematic, kinetic, and neuromuscular behavior, contrary to our hypothesis. It is conceivable that a lower repetition

DISCUSSION

While several prior studies have examined the effects of jump training on healthy athletes as part of ACL injury prevention programs,11,27,36 the efficacy of jump training with athletes after ACL reconstruction remains understudied.7,25,42 Our current trial provides seminal data to improve our understanding of how risk factors for reinjury and osteoarthritis can be reduced in a lasting way through a retraining intervention in a postsurgical population. Our first hypothesis was supported. Jump training had a large effect on improving both patient-reported and performance-based measures of physical function. Further, abnormally high CoI at the start of training decreased throughout the intervention as the participants made desired improvements in hop landing performance, which demonstrates substantial improvements in thigh muscle coordination. Our second hypothesis, however, was not supported. We hypothesized that increased repetition with decreased intensity using BWS would improve retention of these effects, but the data from the current sample did not support this premise in that both groups retained their improvements in all variables. Our third hypothesis was supported, as we demonstrated a decreased risk of joint effusion in those athletes training with BWS.

Before starting training, participants’ self-reported IKDC scores (76.1\% ± 11.5\%) were well below expected values for age- and sex-matched peers (95% ± 9%)3 and athletes at 1 to 2 years after ACL reconstruction (85% ± 10%).12,19 Dramatic gains were made over the course of intervention that were judged clinically meaningful by participants as evidenced by their GRoC scores. A pretraining deficit in SLHD symmetry was improved to reach expected long-term norms for ACL reconstruction7 with training. A recently published study comparing high- and low-intensity jump training 3 months after ACL reconstruction reported a 12-point change in the IKDC, similar to our 13-point change.7 It is notable that the average postoperative timeframe of our participants at a year and a half after surgery
treatment would have yielded poorer retention; however, our object was to pursue best practice dosage parameters based on training tolerance. The small sample in this study serves as a basis for a larger cross-sectional or multigroup study with progressive dosage between groups to explore the relative effects of training intensity and repetition.

While the reductions in impairment and functional level deficits were similar between groups, the improved training tolerance with less risk for knee effusion in the JTBSW group is clinically preferential to training with normal body weight. The patients in the JTBSW group had a statistically higher probability of effusion with training, particularly as repetition increased in weeks 5 through 8. Use of biomarkers to evaluate cartilage degradation with activity may be helpful to determine change in osteoarthritic risk with intervention.9 The reduced training loads provided by BWS13 and the improved training tolerance with high-repetition BWS training suggest that this approach may carry less risk to joint surface health as opposed to traditional training protocols. The improved safety suggests that by using BWS, jump training may be implemented earlier in postoperative recovery. Further study is merited to determine whether early normalization of mechanical and neuromuscular measures can improve long-term outcomes.

The participants in the current trial differ from those in other recent studies, primarily regarding the current participants’ lower pretraining level of function. In recent findings reported in abstract form, participants who were not screened for poor function did not see significant improvements in IKDC scores or SLHD after a jump-training intervention.25 Designating intervention to those patients with less than optimal outcomes is a pragmatic approach for intervention studies as it mirrors clinical reasoning for intervention. Further, the participants in the current trial were, on average, 18 months after surgery, whereas participants in other trials have, on average, within 3 to 6 months from surgery. The participants in the current trial were selected to represent the general population of athletes with poor long-term outcomes after ACL reconstruction, particularly given their heterogeneity in variables such as surgical procedure, surgeon, course of rehabilitation, age, and preferred sport activities.

More than half of patients who undergo ACL reconstruction will show radiographic evidence of knee osteoarthritis within 10 to 15 years after surgery.38 Additionally, in those who return to sport, the rates of incurring a second ACL injury are as high as 1 in 4 patients.39 A result of the current trial indicates a step forward in intervention. A course of directed and individualized jump training is a useful intervention strategy for patients who do not attain their functional goals after ACL reconstruction.

ACKNOWLEDGMENT

The authors thank Dr Curt Hammill and Ms Anna Johnson for assistance with data collection and processing. Dr Jamie Terry for her assistance with treatment fidelity analysis, the athletes who volunteered their time and energy, and clinicians in the community and within the University of Montana who supported the project.

REFERENCES

10. Combs SA, Dugan EL, Ozimek EN, Curtis AB. Bilateral coordination and other long-term problems, particularly in athletes who retain decreased co-contraction in landing. Long-term prospective research is necessary to determine whether the risk of osteoarthritis and reinjury is in fact decreased in patients who undergo extensive jump training. Because patients with less than optimal outcomes after ACL reconstruction are unlikely to improve with time alone and given that long-term sequelae can be debilitating, results of the current trial indicate a step forward in intervention. A course of directed and individualized jump training is a useful intervention strategy for patients who do not attain their functional goals after ACL reconstruction.
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