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# Effects of Neuromuscular Interventions Utilizing External Biofeedback Apparatuses on The Risk And Incidence Of Second Anterior Cruciate Ligament Injuries: A Systematic Review.

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# EFFECTS OF NEUROMUSCULAR INTERVENTIONS UTILIZING EXTERNAL BIOFEEDBACK APPARATUSES ON THE RISK AND INCIDENCE OF SECOND ANTERIOR CRUCIATE LIGAMENT INJURIES: A SYSTEMATIC REVIEW.

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**Abstract**

STUDY DESIGN: Systematic review.

BACKGROUND: Anterior cruciate ligament (ACL) injury is a common orthopedic condition with an estimated rate of 20,000 to 600,000 injuries in the US per year, with higher incidences in athletic and female populations. The rate of re-injury following surgical ACL repair (ACLR) ranges between 13.8-33.3%. Current clinical practice guidelines for ACLR rehabilitation cite inconclusive evidence for definitive outcome measures that accurately determine successful return to sport (RTS). There is a need to establish more effective avenues of rehabilitation interventions to decrease the rate of reinjury, particularly in female athletes. Recent evidence suggests interventions utilizing external biofeedback apparatuses (EBA) in conjunction with neuromuscular rehabilitation decrease the risk of second ACL injury (sACL) after ACLR.

OBJECTIVE: The objective of this systematic review was to investigate the effects of neuromuscular interventions using external biofeedback on the rate and risk of re-injury following ACLR rehabilitation.

METHODS: Five online databases were searched from September 2020 through September 2021. Key terms included ‘ACL rehabilitation,’ ‘female,’ ‘balance,’ ‘proprioception,’ ‘neuromuscular’ ‘reinjury,’ ’rerupture,’ ‘secondary injury.’ This method returned 251 articles and 7 articles were included in this systematic review.

RESULTS: The average PEDRO score of the articles included here is 4.8/10, ranging from 1/10 to 8/10. The articles demonstrated a heterogeneity in the study designs and types of EBA implemented. The conglomerate results suggest there is weak evidence neuromuscular rehabilitation with EBA can reduce the risk of sACL.

CONCLUSIONS: The use of perturbation as a source of biofeedback to augment neuromuscular reeducation may reduce the rate of reinjury following ACLR. The results of this study must be interpreted with caution due to the low quantity and quality of evidence on this subject.

KEY WORDS: ACL rehabilitation, female, balance, proprioception, neuromuscular, reinjury, rerupture, secondary injury.

**Introduction**

Anterior cruciate ligament (ACL) injuries commonly require surgical reconstruction (ACLR), conservative rehabilitation (CR), or both (ACLR+CR). The annual number of ACL injuries in the US is estimated to be between 20,000 - 600,000 and subsequent ACLR of 15.3 - 458.4 per 100,000 people with ACL tears among commercially insured patients in 2014.[1] However, ACLR+CR does not always resolve deficits nor prevent second ACL injuries (sACL). An sACL is defined as a ruptured graft or an ACL injury on the contralateral leg. The incidence of sACL after an initial ACL injury (iACL) has been estimated to range from 13.8% to 33.3%. Essentially, the risk of an ACL injury is higher once an individual has already sustained an ACL injury.[5,6,24] Post ACLR+CR, patients frequently demonstrate deficits in isometric strength, delays in activation of the quadricep and hamstring, and altered rates of muscular force development in knee and hip muscle groups.[2-4] Current evidence suggests these deficits are risk factors for sACL. Other risk factors leading to sACL include asymmetrical landing patterns, lower extremity postural instability, and female sex.[6-8]

Research has long indicated females have an increased risk of ACL injury compared to males.[9] After iACL, females were more likely to exhibit increased gait asymmetries during perturbation and increased knee adduction movement strategies compared to men.[10,11] Additionally, females tend to exhibit higher levels of injury-related anxiety after iACL, an established determinant for readiness to return sport (RTS), and are overall less likely to RTS after iACL compared to their male counterparts.[12,13] With regards to sACL incidence, there is conflicting evidence for sex-based differences despite well-established sex-based differences in deficits post ACLR.[14, 15] Considering the overall high incidence of sACL, and persisting female-specific risk factors and deficits post iACL, females are an important subpopulation to examine in the study of sACL.

The clinical practice guideline (CPG) for the rehabilitation of an ACLR is broken into three distinct phases: impairment-based, sport-specific, then return to play.[16] Neuromuscular control has been established as a central pillar in the rehabilitation of ACLR as altered neuromuscular control could be responsible for sACL. [2, 3, 7, 10, 16-18] The CPG recommends neuromuscular training be added to strength training interventions, but the mode of neuromuscular training is not specified.

The central nervous system (CNS) modulates adaptive changes following ACLR and plays an important role in maintaining sensorimotor control during demanding tasks.[19] As such, it is heavily taxed throughout the re-training of appropriate kinematics during tasks involving the lower extremity kinetic chain.[20] The literature demonstrates the merits of using external forms of biofeedback in order to relieve the CNS of internal attention, which is highly cognitively demanding.[17,20] This allows for the maintenance of improved biomechanics during tasks due to decreased cognitive demand. [17, 20] Common examples of an external biofeedback apparatus (EBA) are slant boards and BOSU balls. Therefore, we hypothesize the use of an EBA to augment neuromuscular training can reduce the rate and risk of sACL.

Due to the increased risk of sACL's in the female population and the lack of guidance regarding specific modes of neuromuscular training in the current CPG, the purpose of this systematic review is to investigate the effect of neuromuscular interventions using an EBA on the rate and risk of sACL in females with a history of ACLR.

**Methods**

A search of the literature from September 2020-September 2021 was conducted using the search engines Embase, PubMed, MEDLINE, CINAHL, and PEDro. The key terms used were 'ACL rehabilitation,' 'female,' 'balance,' 'proprioception,' 'neuromuscular,' 'reinjury,' 'rerupture,' 'secondary injury,'. Inclusion criteria were (1) peer-reviewed studies, (2) female participants, (3) ACL injury with or without other ligamentous injury, and (4) at least one intervention utilizing an EBA. There was not enough literature available with female-only cohorts for a systematic review. If a study's cohort included mixed male and female participants, then the article (5) must demonstrate there was no effect from gender on the results. Exclusion criteria were (1) articles older than 10 years as of September 2020 and (2) failure to meet all inclusion criteria.

The primary outcome measure of this systematic review is incidence of sACL. An sACL is defined as a rupture of a graft post-operatively or an ACL injury on the contralateral leg. of However, literature and empirical data reporting sACL is sparse. Therefore, additional outcome measures of interest were chosen based on recommendations from the 2016 CPG by van Melik et al regarding safe RTS. The most current CPG for ACLR rehabilitation recommends an overall rehabilitation period of 9-12 months, and for the clinician to clear the patient to RTS inorder to prevent sACL. RTS eligibility should be assessed with a battery of LE strength tests, hops tests, LSI of 90-100%, and quality of movement measures.[16] For the 7 articles included in this systematic review, LE strength, functional hops, LSI, and quality of movement outcome measures were considered in addition to incidence of sACL to represent rate and risk of sACL.

**Results**

The initial search retrieved 251 articles. Articles were first subjected to a title screen to ensure they were specific to the knee, and were not dedicated to other conditions (e.g. osteoarthritis, patellofemoral pain, etc.), then a duplicate screen. This resulted in 75 articles. Articles were subsequently screened by abstract then a full text screen for inclusion and exclusion criteria. Twenty-nine articles were reviewed in their entirety. Articles that could not be retrieved in full text or unavailable in English were excluded. This resulted in 4 articles.

A further citation review was performed to ensure a maximally thorough review of the literature. Four articles were retrieved with this method. These articles were assessed through the processes outlined above, and 3 were included for a total of 7 articles. A summary of this process can be referenced in Figure 1.

Figure 1. PRISMA Diagram

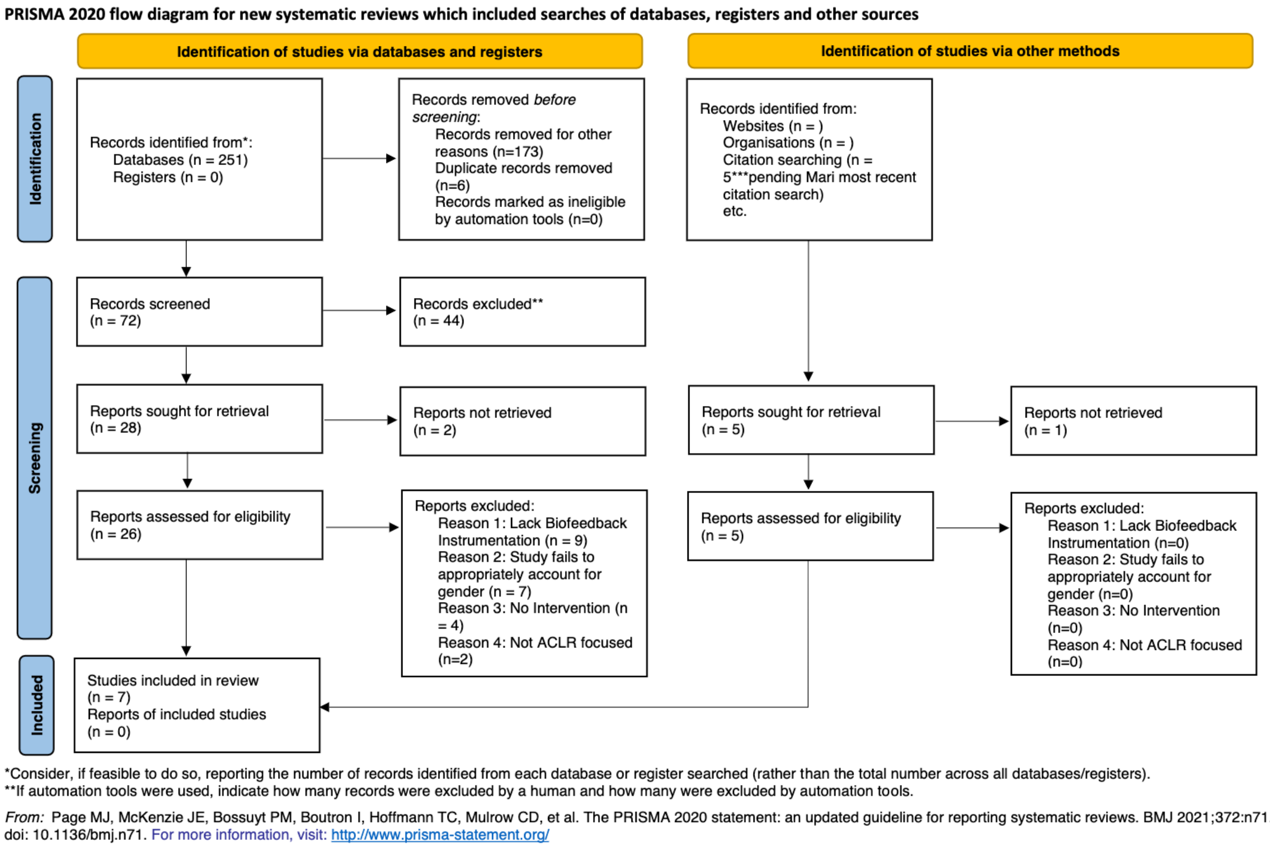


Table 1 presents the experimental design and interventions of each of the 7 articles included in this systematic review. The average PEDRO score of the articles is 4.8 and ranges from 1/10 to 8/10. All articles were of a randomized control/clinical trial experimental design. However, these articles presented with heterogeneity in several aspects and introduced a chance for uncontrolled variables in our results.

Each study used a form of biofeedback, which is defined as an external application of a stimulus applied in order to modify neuromotor output. As this is a new and expanding area of research, there is a significant amount of variability in intervention. The studies featured whole body vibration therapy, perturbation training, balance training augmented with bosu/airex, education in conjunction with hip based perturbation, and bracing. Three articles (Capin, Failla et al, Johnson et al, Capin, Zarzycki et al) had female-only participants, while the remaining 4 were of mixed gender. Additionally, Palm et al did not use a distinct control group, instead comparing the effects of its intervention against the uninjured leg of the subjects.[28] Table 2 presents the variability present in the duration of interventions, follow-up timeframe, and stage of rehabilitation. Further, given that the majority of graft ruptures occurring within 2 years of reconstruction, not all studies included enough follow-up time to adequately capture all sACL injuries.[21, 28]

Table 1. Overview of experimental design and interventions of articles.

| **Author** | **Experimental Design** | **PEDro Score** | **Biofeedback Sample Size** | **Control Sample Size** | **Biofeedback Intervention** | **Control Intervention** |
|---|---|---|---|---|---|---|
| Fu et al[23] | RCT | 7/10 | 24 | 24 | EX + WBVT | EX |
| Johnson et al[24] | RCT | 6/10 | 19 | 20 | EX (SAPP) + perturbation | EX (SAPP) |
| Capin, Failla et al[25] | RCT | 5/10 | 18 | 18 | EX (SAPP) + perturbation | EX (SAPP) |
| Kawashima et al[21] | RCT | 4/10 | 153 | 136 | HIP-GREAT | EX |
| Nagelli et al[26] | RCT | 3/10 | 18 | 10 | NMR with BOSU, airex | NMR with BOSU, airex with uninjured controls |
| Capin, Zarzycki et al[27] | RCT | 8/10 | 18 | 18 | EX (SAPP) + perturbation | EX (SAPP) |
| Palm et al[28] | RCT | 1/10 | 58 | 58 (uninjured LE of each individual) | EX + knee brace | EX |

WBVT = whole body vibration training; SAPP = strengthening, agility, plyometrics, prevention; HIP-GREAT = hip-focused injury prevention training + graft rupture education and avoidance training; NMR = neuromuscular rehabilitation.

Table 2. Overview of treatment parameters and time

| Author | Intervention Duration | Follow-up Duration | Time from ACLR at Enrollment |
|---|---|---|---|
| Fu et al[23] | 2x/week for 8 weeks | 6 months | 1 month s/p ACLR |
| Johnson et al[24] | 2x/week for 5 weeks | 2 years | <9 month s/p ACLR |
| Capin, Failla et al[25] | 2x/week for 5 weeks | 2 years | 6 +/- 2 months s/p ACLR |
| Kawashima et al[21] | 9 months cumulative | 3 years | 0 month s/p ACLR |
| Nagelli et al[26] | 12 sessions cumulative | N/A | 7.7 +/- 3.7 month s/p ACLR |
| Capin, Zarzycki et al[27] | 2x/week for 5 weeks | 2 years | 12 weeks - 10 month s/p ACLR |
| Palm et al[28] | 1 session | N/A | 0 month s/p ACLR |

Three of the 7 included articles found significant differences in outcome measurements when comparing EX to EX + EBA interventions. In Fu et al,[23] the implementation of whole body vibration training (WBVT) demonstrated increased hamstring and quadriceps torque and improved 1-legged hop distance compared to the control. In Capin, Zarzycki el al,[27] the SAPP + perturbation group protocol demonstrated increased hip internal abduction moments and knee internal extension moments at PFKA compared to the SAPP only group during post-training gait testing. In Palm et al,[28] significantly increased OSI were found in ACLR patients wearing a knee brace. In Nagelli et al,[26] the study compared post-training knee biomechanics in participants with and without an ACL injury after both groups completed an NMR protocol. The study found the injured group performed similarly to the uninjured control group in all outcome measures except for knee abduction angle during initial contact during gait analysis.[26]

Three of the 7 included articles failed to reach significance in the predetermined outcome measures when comparing EX to EX + EBA interventions.[21, 24, 25] There was no significant difference in incidence of sACL in the Johnson et al[24] protocol comparing SAPP to SAPP + perturbation. In Capin, Failla et al,[25] SAPP to SAPP + perturbation were compared and found no significant difference in quadricep strength nor functional hops. In Kawashima et al,[21] EX to HIP=GREAT protocol were compared and the study failed to reach significance in quadricep and hamstring strength, and with incidence of sACL.

Table 2. Evidence and outcome measures by study

| Author | Biofeedback Intervention | Control Intervention | Outcome Measure | Biofeedback | Control | P value |
|---|---|---|---|---|---|---|
| Fu et al[23] | Whole body vibration + EX | EX | Peak torque HS 6 mo post-op, affected limb (N(m)) | | | |
| | | | 60 deg/s (LSI%) | 92.4 ± 23.1 (89.1) | 87.2 ± 19.4 (87.8) | 0.045 |
| | | | 180 deg/s (LSI%) | 71.6 ± 16.2 (88.1) | 66.5 ± 21.9 (87.4) | 0.07 |
| | | | 300 deg/s (LSI%) | 58.6 ± 18.0 (85.9) | 51.5 ± 13.9 (78.7) | 0.014 |
| | | | Peak torque quads 6 mo post-op, affected limb (N(m)) | | | |
| | | | 60 deg/s (LSI%) | 139.7 ± 32.4 (90.8) | 120.0 ± 34.9 (81.5) | 0.012 |
| | | | 180 deg/s (LSI%) | 98.9 ± 22.4 (85.2) | 90.0 ± 22.2 (82.8) | 0.013 |
| | | | 300 deg/s (LSI%) | 65.5 ± 17.5 (86.5) | 56.8 ± 22.9 (77.4) | 0.005 |
| | | | 1-legged hop, cm (LSI %) | 140.8 ± 27.1 (91.2) | 129.5 ± 38.4 (87.1) | 0.022 |
| | | | Triple hop, cm (LSI%) | 381.2 ± 59.5 (90.1) | 365.2 ± 49.4 (87.6) | 0.345 |
| Johnson et al[24] | EX (SAPP) + perturbation | EX (SAPP) | Incidence of sACL, n(%) | 4(21) | 5(25) | 0.77 |
| Capin, Failla et al[25] | EX (SAPP) + perturbation | EX (SAPP) | Quad strength LSI (%) | | | |
| | | | 1 year | 100 ± 14 | 94 ± 9 | 0.414 |
| | | | 2 year | 102 ± 14 | 101 ± 13 | |
| | | | Single-hop LSI (%) | | | |
| | | | 1 year | 100 ± 11 | 98 ± 7 | 0.375 |
| | | | 2 year | 101 ± 9 | 97 ± 10 | |
| | | | Crossover-hop LSI (%) | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | 1 year | 97 ± 8 | 99 ± 6 | 0.181 |
| | | | 2 year | 97 ± 8 | 101 ± 6 | |
| | | | Triple-hop LSI (%) | | | |
| | | | 1 year | 97 ± 4 | 101 ± 5 | 0.188 |
| | | | 2 year | 99 ± 6 | 100 ± 5 | |
| | | | 6-m timed hop LSI (%) | | | |
| | | | 1 year | 102 ± 4 | 103 ± 5 | 0.725 |
| | | | 2 year | 100 ± 5 | 98 ± 7 | |
| Kawashima et al[21] | HIP-GREAT | EX | Quad strength LSI (%) | 91.5 ± 11.9 | 91.8 ± 11.5 | 0.83 |
| | | | HS strength LSI (%) | 91.0 ± 11.1 | 89.3 ± 8.3 | 0.14 |
| | | | Incidence of sACL, n(%) | 5(3.3) | 10(7.4) | 0.09 |
| Nagelli et al[26] | NMR with BOSU, airex | NMR with BOSU, airex with uninjured controls | IC flexion angle (°) | 24.9 ± 9.0 | 22.0 ± 8.0 | Not significant |
| | | | IC flexion moment (Nm/kg) | 0.36 ± 0.05 | 0.33 ± 0.08 | Not significant |
| | | | IC abduction angle (°) | 2.4 ± 3.3 | 20.6 ± 2.5 | 0.002 |
| | | | IC abduction moment (Nm/kg) | 0.03 ± 0.04 | 0.02 ± 0.02 | Not significant |
| | | | LSI (%) | Pre and post training LSI was calculated for sagittal knee kinematics (knee flexion angle and moment) of ACLR group at IC and peak. There was no significant change in LSI. | | |
| Capin, Zarzycki et al[27] | EX (SAPP) + perturbation | EX (SAPP) | PKFA, involved LE (°) | | | |
| | | | Post-training | 20.1 | 19.5 | Not significant |
| | | | Hip internal extension moment at PKFA, involved LE (Nm/kgm) | | | |
| | | | Post-training | 0.32 | 0.31 | Not significant |
| | | | Hip internal abduction moment at PKFA, involved LE (Nm/kgm) | | | |
| | | | Post-training | 0.59 | 0.54 | <0.05 |
| | | | Knee internal extension moment at PKFA, involved limb (Nm/kgm) | | | |
| | | | Post-training | 0.43 | 0.35 | <0.05 |
| Palm et al[28] | EX + knee brace | EX | OSI | | | |
| | | | ACL rupture | 2.9 ± 1.3 | 3.7 ±1.5 | <0.001 |
| | | | No ACL rupture | 2.8 ± 1.3 | 3.0 ± 1.1 | 0.17 |

WBVT = whole body vibration training; SAPP = strengthening, agility, plyometrics, prevention; HIP-GREAT = hip-focused injury prevention training + graft rupture education and avoidance training; NMR = neuromuscular rehabilitation; LSI = limb symmetry index; IC = initial contact; PFKA = peak knee flexion angle; OSI = overall stability index.

**Discussion**

Based on the articles reviewed, interventions prescribing NMR with EBA inconsistently impacted the risk and rate of sACL. The majority of literature reviewed was not of a quality from which to create well informed guiding recommendations. Of the 251 articles screened for inclusion here, only 7 demonstrated high enough internal and external validity to include in this systematic review, and of those 7 only 3 demonstrated the level of bias control necessary to draw conclusions from.[23,24,27] This demonstrates that the available literature on this subject is not of the quality needed to guide practice. With consideration to that fact, the best conclusion with respect to all three pillars of evidence based practice including clinical judgment, experience, and the best available evidence, there is likely benefit to performing neuromuscular interventions augmented with biofeedback.

Clinics may benefit from including specific exercises following ACLR in order to maximize bilateral stability and minimize the risk of reinjury. The best available evidence indicates that perturbation and the use of unstable surfaces such as airex and Bosu could be incorporated into interventions targeting ACLR as a strategy for improving rate of recruitment in the quadriceps and hamstring, as well as potentially decreasing the overall rate of graft rupture. Passive interventions such as WBVT and the application of a knee brace with activity may also improve performance following ACLR. WBVT demonstrates improved isokinetic performance as measured by peak torque for the hamstrings and quadriceps at 6 months postoperatively, while the application of a knee brace improved postural stability. Care should be taken with passive interventions as there is little maintenance of gains from treatment following the cessation of the passive intervention.

Limitations in this study include a low quality and quantity of existing research on this subject. As this is an emerging area of practice and research, there was a great deal of variability in the mode of biofeedback used for intervention.

The strength of this systematic review is limited by the lack of study designs with exclusively female samples. This was addressed by accepting a ‘no difference’ statement of statistical analysis indicating that gender differences were statistically assessed for but not found. However, given that it has been previously established that women are more susceptible to ACL injury and less likely to respond to intervention, there is reason for skepticism that the ‘no difference’ statement on gender analysis represents a true negative in all cases.[10]

Further, the heterogeneity present in the patient populations studied represents a barrier to clear understanding of the real risk of re-injury, as rates of reinjury are known to increase with young, highly active athletes.[7,8,24] The populations recruited for these studies varied from high level young athletes to the general population, with average ages ranging from 16.0 +/- 3.7 years to 25.2 +/- 7.3 years. The graft rupture rate reported for young active athletes ranges as high as 33.3%, while the rate for less active individuals >20 is reported at 18%.[7,28]

Additionally, there was undesirable heterogeneity in study design, with one study performing repeated measures within subjects design rather than between subjects design and using uninjured controls rather than a control group similar to the experimental group at baseline.[28] Significant variation was also noted in the application of biofeedback. As seen in Table 1, the modes of biofeedback clinically used in ACLR rehabilitation included the use of knee bracing, perturbation, NMR with unstable surface including Bosu and airex, strategies focused on the hip with education on graft rupture prevention, and whole body vibration.

Further, there was variation in the nature of its use. Two studies, Palm et al and Fu et al,[23,28] use biofeedback passively, while the other studies included use biofeedback actively. Active use of biofeedback allows an opportunity for altered neuromuscular output in response, while passive does not. Thus, active use of biofeedback offers a more valuable opportunity for retraining the rate and force at which the lower kinetic chain responds to concentric and eccentric demands at varying speed and intensity compared to passive use of biofeedback. This represents a further source of heterogeneity in the studies included.

Lastly, it is important to re-emphasize the literature regarding appropriate objective measures to determine readiness to RTS remains weak. There are currently no well-supported measures that have been found to reliably predict sACL injuries. Van Melik recommends further prospective studies to validate objective measures and further RTC's to guide clinical decision making for readiness to RTS post-ACLR.[16]

**Conclusion**

The number of iACL injuries in the general population is estimated to be between 20,000-600,000.[1] Following an iACL injury, the percentage of reinjury increases to 13.8%, and with subsequent exposure to high level athletic activity may increase as high as 33%.[5,6,24] Best available evidence suggests that exercises using external perturbation, or internal perturbation through the use of unstable surfaces such as bosu balls, in service of neuromuscular reeducation may improve rehabilitation following ACLR by reducing the rate of reinjury. Further, performing all rehabilitative exercises bilaterally as opposed to limiting focus to the operative extremity may have a protective effect in limiting reinjury. The ACL-SPORTS trial in particular demonstrated a nominal increase in rate of reinjury despite a near 100% rate of return to sport at pre-injury levels.[24] The strength of these recommendations is limited due to the low quantity and quality of research on this topic, and the results should be applied with caution using clinician's best judgment.

**Key Points**

Findings: The percentage rate of reinjury after ACLR remains high with standard rehabilitation. The addition of neuromuscular reeducation with biofeedback, especially through the use of perturbation, represents a promising avenue to reduce the rate of re-injury.

Implications: Neuromuscular reeducation with biofeedback should be incorporated into standard rehabilitation after ACLR, especially exercises with a focus on challenging stability with external perturbations or unstable surfaces such as bosu balls.

Caution: the quantity and quality of research in this area are presently low, and as a result the findings of this study must be considered with caution.

**Study Details**

Author Contributions: All authors contributed to the review process, writing process, and editing process.

Data Sharing: All data relevant to the study are included in the article.

Public Involvement: Acknowledgement and thanks to the University of Texas at El Paso library department for their assistance with the literature search and study retrieval process.

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