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Reactive Strength as a Metric for Informing Return-to-Sport Decisions: A Case-Control Study

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Objective: Current return-to-sport decisions are primarily based on elapsed time since surgery or injury and strength measures. Given data that show rates of successful return to competitive sport at around 55%, there is strong rationale for adopting tools that will better inform return to sport decisions. The authors' objective was to assess reactive strength as a metric for informing return-to-sport decisions. ***Design:*** Case-control design. ***Methods:*** Fifteen elite athletes from national sports teams (23 [6.0] y) in the final phase of their return-to-sport protocol following a unilateral knee injury and 16 age-matched control athletes (22 [4.6] y) performed a unilateral isometric strength test and 24-cm drop jump test. Pairwise comparisons were used to determine differences between legs within groups and differences in interleg asymmetry between groups. ***Results:*** Strength measures did not distinguish the control from the rehabilitation group; however, clear differences in the degree of asymmetry were apparent between the control and rehabilitation groups for contact time (Cohen $d = 0.56$; −0.14 to 1.27; 8.2%; $P = .113$), flight time ($d = 1.10$; 0.44 to 1.76; 16.0%; $P = .002$), and reactive strength index ($d = 1.27$; 0.50 to 2.04; 22.4%; $P = .002$). ***Conclusion:*** Reactive strength data provide insight into functional deficits that persist into the final phase of a return-to-sport protocol. The authors' findings support the use of dynamic assessment tools to inform return-to-sport decisions to limit potential for reinjury.

Keywords: drop jump, asymmetry, leg press, elite athlete

Return-to-sport decisions are an important component of sports medicine practice and both researchers and clinicians have attempted to develop evidence-based models to facilitate positive outcomes.[1,2] However, the effectiveness of current rehabilitation and return-to-sport practices should be closely examined given that reinjury rates as high as 49%[3] and less than ideal return-to-sport rates[4] have been reported. In football, players with knee joint trauma were reported to be 3.1 times likelier to suffer a similar injury the following season.[5] A meta-analytical review reported that only 65% of patients return to preinjury level of sport participation following ACL reconstruction surgery, and only 55% return to a competitive level.[6]

Key Points

- A 24-cm unilateral drop jump test performed during the final phase of rehabilitation identified a persistent functional deficit.
- Contact time was clearly increased and flight time clearly decreased in the injured leg of athletes in their final phase of a return-to-sport protocol following knee injury.
- Reactive strength measurement identified functional deficits in the rehabilitation group that suggests it may be a valuable metric for informing return-to-sport decisions.

Three elements define the return-to-sport continuum: (1) return to participation, athlete is physically active, but not ready to return to sport; (2) return to sport, athlete has returned to sport, but is not performing at the desired level; and (3) return to performance, athlete has returned to or exceeded preinjury level of performance.[7] National-level and professional athletes in rehabilitation most commonly aspire to return to performance. An accepted paradigm for the rehabilitation process identifies 3 phases. Specifically, patients are required to demonstrate proficiency in control of volitional muscle contractions, restored reflex responses, and finally, the ability to execute high-speed coordinated muscle actions necessary to perform complex tasks.[8] As part of the return-to-sport decision process, a range of assessment tools are implemented clinically to determine muscular proficiency and coordination, including one-legged hop tests,[9,10] stepdown tests,[11] and associated measures of asymmetry.[12] A review that focused on muscle strength and hop performance concluded that commonly used return to performance muscle function criteria are not sufficiently demanding or sensitive to ensure positive outcomes, defined here as a return to preinjury level of participation.[7,13]

It is therefore apparent that assessment protocols, consisting of demanding and sensitive tests of neuromuscular function (ie, the ability to produce controlled movement through coordinated muscle activity), are required to enable practitioners to make informed return-to-sport decisions. There remains debate regarding the validity of tests in determining the readiness of athletes to return-to-sport.[4] Both increased[14] and decreased injury incidence[15] have been reported when adhering to return-to-sport protocols. Both time (85%) and strength (41%) have been identified as the most common return-to-sport criteria implemented in research following ACL reconstruction,[16] with both isokinetic and isometric

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tests and their associated limb symmetry indices commonly reported. In contrast, only 20% of return-to-sport decisions included performance-based criteria (ie, agility, proprioception, aerobic endurance, quality of motion, completion of a specific program), only 13% assessed single leg hopping, and only 0.48% (one out of 209 studies) used a drop jump (DJ) protocol to inform rehabilitative outcomes.[16]

A DJ assesses the short latency response of the spinal stretch reflex, which in turn modulates muscular stiffness and elastic storage capacity.[17] While a single-legged DJ can provide information on reflex responses, it also captures information relating to rapid force production that has been proposed as an adjunct measure to support return-to-sport decisions.[18] Movement patterns during a DJ have also been identified as being associated with knee valgus angles during cutting movements[19] and performance indicators in contact sport[20] in high-level athletes. Thus, we hypothesized that a reactive strength metric obtained from a unilateral DJ may provide a more relevant and informative metric to assess neuromuscular function and return-to-sport capability following lower limb injury when compared with the typically assessed isometric strength. Specifically, reactive strength derived from a unilateral DJ could be used to assess the rehabilitative process through proficiency in volitional muscle contractions, reflex response, and the ability to execute high-speed coordinated muscle actions.

Methods

Design

Q7 This study was a case-control design, approved by the institutional ethics committee (XXXXX) and adhered to the ethical standards of the Declaration of Helsinki. Written informed consent to participate Q8 was obtained from all participants. Neither patients nor the public were involved in the design, conduct, reporting, or dissemination plans of our research.

Participants

Q9 Participants were identified from the National Sports Institute of Q10 XXXX. Fifteen elite XXX athletes (14 males and 1 female; age 23 [6.0] y) with a unilateral knee injury met the inclusion criteria of having a diagnosis code involving a rupture, sprain, or strain involving the cruciate or medial collateral ligament of the knee, or involving an injury to multiple structures of the knee (International Classification of Diseases 11 codes NC93.30, NC93.50, and NC93.60-62), and who were seen at the clinic between January 2017 and January 2018, were recruited during the third (and final) phase of their return-to-sport protocol. Specifically, the athletes were at the phase in their rehabilitation where they are required to demonstrate the ability to execute high-speed coordinated muscle actions associated with complex tasks.

The athletes in this rehabilitation group were from a range of sports: football (n = 8), martial arts (n = 3), basketball (n = 2), Q11 hockey (n = 1), and cricket (n = 1), and included Olympians as Q12 well as regional and world champions. Sixteen age-matched, noninjured elite XXX athletes (14 males and 2 females; age 22 [4.6] y) from national football (n = 12) and diving (n = 4) teams were also recruited to serve as a control group. All of the football players were outfield players, with no goalkeepers included. The legs of the noninjured athletes were classified as dominant and nondominant, whereas the legs of the injured athletes were classified as injured or noninjured.

Procedures

Unilateral DJ Test. Following a standardized 20-minute warm-up that consisted of jogging and dynamic stretching, the participants were given a visual demonstration of the 24-cm single leg DJ procedure and were instructed to minimize their ground contact time while jumping as high as possible. The use of a 24-cm box has been proposed to be high enough to stress the stretch-shortening cycle, while allowing participants to emphasize a short ground contact time.[21] Athletes were allowed 2 practice jumps before being asked to perform 3 trials with 1-minute recovery between trials, landing on a 4 load cell force plate collecting at 600 Hz (400 Series Performance Force Plate, Fitness Technology, Australia). Athletes were required to Q13 hold their hands on their waist during testing, and were wearing their habitual sports shoes. The force plate was interfaced with computer software (Ballistic Measurement System, Fitness Technology, Australia) that allowed direct measurement of force–time characteristics (peak force, jump height [derived from flight time], contact time, and a reactive strength index [ratio of flight time to contact time]). The dominant or noninjured leg was tested first, and no performance feedback was provided during the testing. The average of the 3 measures were recorded for subsequent analyses. Reliability of single leg DJ has previously been established in athletes with moderate to good ICC values (.70–.84) and acceptable coefficients of variation (5.1%–6.7%) for reactive strength measures.[22]

Unilateral Isometric Leg Press Test. An isometric unilateral leg press test was then performed using an instrumented leg press machine (Compass 530; Proxomed Medizintechnik GmbH, Alzenau, Germany) to assess maximal strength. The athletes were instructed to perform the isometric single leg press with maximum effort for 5 seconds at 90° of knee flexion. Athletes completed 3 trials per leg with 2 minutes of rest between trials, testing the dominant or noninjured leg first. No performance feedback was provided during the testing. A position of 90° was selected given that quadriceps activity is significantly greater for weight-bearing exercises when knee angles exceed 80°.[23] The greatest force was recorded for subsequent analysis.

Statistics

Descriptive statistics are reported as mean (SD) unless stated otherwise. A 4×1, one-way analysis of variance (dominant, nondominant, injured, and uninjured) was performed. Asymmetry data were analyzed using pairwise comparisons to determine differences between the injured versus noninjured legs in the injured group and dominant versus nondominant legs in the control group. Statistical significance was set at $P \leq .05$ in all analyses. To interpret practical meaningfulness, magnitudes of the standardized effects were calculated using Cohen *d* with 95% confidence intervals. Cohen *d* magnitudes were interpreted using thresholds of 0.2, 0.5, and 0.8 for small, moderate, and large.[24] An absolute effect size of 0.2 was considered the smallest worthwhile change, with smaller effects considered trivial. Any effect was deemed unclear if its 95% confidence interval overlapped the thresholds for both small positive and negative effects.

Results

The data for the maximum unilateral isometric strength and peak force produced during the unilateral DJ demonstrated no significant differences between legs in the rehabilitation and control groups Q14 ($F_{3,58} = 0.82$; $P = .48$; Table 1). The identified SWCs were 9.5 kg and 99.5 N. The degree of asymmetry also did not differ significantly between groups.

The analysis of variance identified a significant difference in jump height ($F_{3,58} = 10.75$; $P < .01$) with a SWC of 0.73 cm. In the control group, unilateral jump height calculated from flight time was not significantly different between the dominant (13.9 [3.9] cm) and nondominant (12.8 [3.4] cm) legs; however, differences were apparent between the injured (7.8 [2.6] cm) and noninjured (11.7 [3.2] cm) legs in the rehabilitation group ($P = .0009$). The difference in leg asymmetry between the 2 groups was large ($d = 1.20$; 0.55 to 1.86; $P = .0008$).

Contact time, flight time, and reactive strength index data are presented in Figure 1. Analysis of variance results indicated no significant differences between contact times ($F_{3,58} = 2.1$; $P = .11$); however, significant differences were seen in flight time Q15 ($F_{3,58} = 13.7$; $P < .01$) and RSI ($F_{3,58} = 16.1$; $P < .01$). No significant differences were seen between legs in the uninjured control group for any of these variables ($P > .31$), with SWCs of 9 ms, 9 ms, and 40 arbitrary units identified for contact time, flight time, and RSI, respectively. Clear differences in the degree of asymmetry were apparent between the control and rehabilitation groups for flight time ($d = 1.10$; 0.44 to 1.76; 16.0%), and reactive strength index ($d = 1.27$; 0.50 to 2.04; 22.4%).

Discussion

Q16 Maximal unilateral isometric strength and peak force during a unilateral DJ could not be distinguished between legs of individuals, with comparable levels of symmetry between a control and rehabilitation group of national-level athletes returning to sport following knee injury. In contrast, clear and significant differences in the degree of asymmetry in flight time and reactive strength from unilateral DJs were indicative of functional limitations. The persistence of these limitations into the final phase of a return-to-sport protocol provides justification for the use of dynamic assessment tools to inform return-to-sport decisions, which could in turn limit potential for reinjury.

While it has previously been reported that muscle strength is a critical return-to-sport criterion[25] and quadriceps strength is likely an important prerequisite to prescription of single-leg tasks,[26] it is clear that typical maximal force production measures struggle to detect meaningful functional deficits. In male professional soccer players, no significant difference in maximal voluntary isometric contraction values during an isometric leg press at 80° of knee flexion were observed pre, 6-month post, and 12-month post reconstructive ACL surgery within and between injured and uninjured legs.[27] Our findings also indicate no difference in maximum values when compared against a control group of age-matched, noninjured elite athletes, refuting the existence of bilateral deficit in quadriceps maximal activation in our cohort; however, we acknowledge the lack of any preinjury data for comparison. In young athletes, symmetrical muscle function (>90% symmetry index) in hop tests and knee-flexion and knee-extension tests exhibited no association with the likelihood of sustaining a subsequent knee injury; however, return to sport earlier than 9 months substantially increased injury risk.[28] Thus, our data add to earlier work in demonstrating that commonly used muscular strength tests are likely not sufficiently demanding to assess the attainment of sport-appropriate neuromuscular function postinjury.[13]

In contrast, the rate of force development (RFD) has been described as one of the most important physical qualities in sport-specific actions and muscular force produced rapidly (<200 ms) has been linked to a reduced injury risk.[29] It has been suggested that the ability to attenuate, regenerate, and redirect forces acting on a single limb are likely relevant in an injury risk context.[30] Angelozzi et al[18] clearly showed deficits in isometric RFD that persisted despite maximal force production capacity being comparable with pre-ACL surgery levels and the uninjured side. In an interesting adjunct to the work by Beischer et al,[28] at least 12 months was required to attain RFD levels at 30, 60, and 90 ms that exceeded 90% of the preinjury levels. Given these RFD data and the fact that return to sport >9 months after surgery is reported to substantially reduce reinjury rates,[31] it is of concern that over 80% of all studies in a recent scoping review allowed return to sport prior to 9 months.[16]

The ability to produce force rapidly is dynamically taxed in a unilateral DJ.[32] Thus, the DJ test has the potential to provide important information on neuromuscular deficits that may compromise return to sport by challenging the reactive capacity of the neuromuscular system during the rapid transition from eccentric to concentric work. Here, we present support for substantial deficits in reactive strength persisting in the absence of strength imbalances characteristic of return-to-sport decision-making protocols. The unilateral DJ also provides an indirect measure of neuromuscular control and the short latency component of the stretch reflex and protective inhibition.[33] There is evidence for altered afferent proprioceptive information following knee ligament damage[34,35]

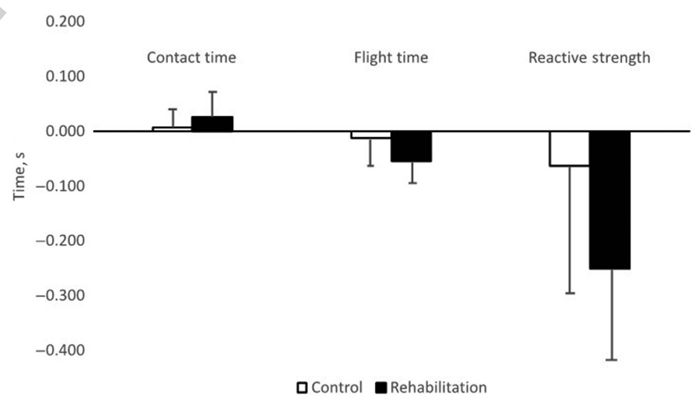

Figure 1 — Differences in leg symmetry between the control and rehabilitation groups. N.B reactive strength is dimensionless and represents the ratio of flight time to ground contact time.

Q17 **Table 1 Between-Group Comparisons of Isometric and Dynamic Force-Generating Capability**

	Rehabilitation group (n = 15)		Control group (n = 16)	
	Injured	Noninjured	Dominant	Nondominant
Unilateral isometric leg press, kg	157.2 (60.7)	174.7 (52.6)	168.1 (37.9)	165.4 (33.1)
Peak force unilateral drop jump, N	2577.6 (618.3)	2618.2 (593.8)	2383.3 (367.2)	2418.6 (384.4)

and 3D motion analysis has identified long-lasting[36] biomechanical differences in a unilateral task. Suppressed preparatory muscle activation patterns in the 150 ms prior to landing have also been demonstrated following lower limb injury that would impact DJ performance, expose the limb to additional load, and potentially modulate injury risk.[37]

The current DJ test is easy to administer, clinically applicable, and could be widely adopted in practical settings given the ability of mobile telephone applications to accurately and reliably assess contact time and flight time in DJs when compared with a force plate measuring at 1200 Hz.[38] This ease of assessment for the DJ is important given the limited application of 3D motion capture in clinical settings.[39] While the unilateral DJ may not identify the exact nature of dysfunction, the task may be sufficiently demanding to provide a global picture of overall function to inform return-to-sport decisions. Thus, the unilateral DJ could be integrated into test batteries alongside contextual factors, time from injury, clinical examinations, and other tests that have been positively related to rehabilitation outcomes, such as vertical force stabilization time following a 19 cm stepdown[11] and the 6-m timed hop test.[40]

Despite the limb symmetry index coming under scrutiny in recent years and questions raised regarding its efficacy as a return-to-sport criteria,[41] our rehabilitation group exhibited greater asymmetry during the single-leg DJ task. Rather than questioning the use of the limb symmetry index as return-to-sport measure, we propose that the tests used in deriving this index may need revisiting. The most common elements included in return-to-sport test batteries are quadriceps strength and hop tests for function, with a limb symmetry index of ≥90% used as pass threshold.[4] Current evidence suggests that passing return-to-sport test batteries overall has minimal effect on reducing the risk of subsequent ACL injuries,[4,42] raising uncertainty in the clinical value and validity of current protocols. Altered neuromuscular control at the hip and knee during a drop vertical jump has been prospectively linked with the incidence of primary[43] as well as secondary[44] ACL injury in athletes, further supporting the value of using DJ tasks in the management of knee injuries.

The data presented here that indicate substantial deficits in reactive strength can inform rehabilitation programs for athletes in the late stages of their return-to-sport progression. Specifically, exercises designed to elicit rapid responses from the neuromuscular system are likely to enhance rehabilitative outcomes. Work in elite athletes has shown that unexpected disturbance training can improve strength, sensorimotor function, and proprioception[45]; however, a range of exercises designed to invoke rapid motor unit activation will likely prove beneficial in decreasing the functional deficits observed in reactive strength. It is also worth noting that psychological training should form a major component of return-to-sport protocols, given that kinesiophobia has been a commonly cited reason for not returning to sport[46] and that positive psychological states have been linked to a successful return to sport.[47] It has also been acknowledged that tests of muscle function often do not align well with the patients' experiences and self-reported measures.[13] Future research may enable a closer coherence between functional return-to-play assessments, such as reactive strength with perceptions of functional capacity and fear of reinjury.

Conclusion

Reactive strength data provided insight into functional deficits that persisted into the final phase of a rehabilitation program. Our preliminary findings support the use of dynamic assessment tools to inform return-to-sport decisions to limit potential for reinjury. Specifically, substantial asymmetry in reactive strength performance obtained from a 24-cm unilateral DJ may assist in informing return-to-sport protocols.

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Queries

Q1. As per journal style, “mean ± SD” should be represented as “mean (SD).” Hence, the values are changed accordingly throughout the article. Please check and confirm.

Q2. As per journal style, repeats of words in article and journal title are not allowed in keywords. Hence, the keyword "rehabilitation" was deleted.

Q3. Please check the placement of key points.

Q4. Please note that there is a mismatch noticed in the author name between manuscript (Kim Hébert-Losier) and meta-page/data (Kim Hebert-Losier). Please check and confirm which one has to be followed in this regard?

Q5. Please ensure author information is listed correctly here and within the byline.

Q6. Please provide the expansion for "ACL."

Q7. Please update "XXX" in the sentence "This study was a . . . ."

Q8. Please check whether the changes to the sentence beginning “Neither patients ... ” preserve the intended meaning.

Q9. Please update "XXX" in the sentence "Participants were identified from ... ."

Q10. Please update "XXX" in the sentence "Fifteen elite ... ."

Q11. Please check whether the changes to the sentence beginning “Sixteen age-matched ... ” preserve the intended meaning.

Q12. Please update "XXX" in the sentence "Sixteen age-matched ... ."

Q13. Please provide the city name for "Fitness Technology."

Q14. Please provide the expansion for "SWC."

Q15. Please provide the expansion for "RSI."

Q16. Please check the edit made in the sentence “Maximal unilateral ... ” and correct if necessary.

Q17. Please provide the first column heading for Table 1.

Q18. Please check whether the changes to the sentence beginning “Suppressed preparatory ... ” preserve the intended meaning.

Q19. Please check the edit made in the sentence “Current evidence ...” and correct if necessary.

Q20. Please check whether the changes to the sentence beginning “Neither patients ... ” preserve the intended meaning.

Q21. Please provide the year, volume number and page range for the Ref. 45.