

# Effect of Quadriceps and Hamstring Strength Relative to Body Weight on Risk of a Second ACL Injury

## A Cohort Study of 835 Patients Who Returned to Sport After ACL Reconstruction

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**Background:** Anterior cruciate ligament (ACL) injuries are common sports-related injuries with a high risk of reinjury after return to sport (RTS). Rehabilitation aims to regain symmetrical knee strength and function to minimize the risk of a second ACL injury after RTS.

**Purpose:** To determine the effect of absolute quadriceps and hamstring strength, normalized by body weight, on the risk of a second ACL injury during the first 2 years after RTS in patients who have undergone ACL reconstruction (ACLR).

**Study Design:** Cohort study; Level of evidence, 3.

**Methods:** Data from patients after index ACLR at the time of RTS were extracted from a rehabilitation registry—Project ACL. Patients who had performed isokinetic tests for quadriceps and hamstring strength and hop tests before RTS were included. The endpoint was a second ACL injury or a follow-up of 2 years after RTS after ACLR.

**Results:** A total of 835 patients (46% women), with a mean age of  $23.9 \pm 7.7$  years, were included. During the study period, 69 (8.3%) second ACL injuries (ipsilateral and contralateral) occurred. Greater relative quadriceps strength in the injured leg increased the risk of a second ACL injury (relative risk [RR], 1.69 [95% CI, 1.05-2.74];  $P = .032$ ). In patients who had recovered symmetrical quadriceps strength (limb symmetry index  $\geq 90\%$ ), there was no effect of quadriceps strength on the risk of second ACL injury (RR, 1.33 [95% CI, 0.69-2.56];  $P = .39$ ). Quadriceps strength on the healthy side or hamstring strength, regardless of side, had no effect on the risk of a second ACL injury.

**Conclusion:** Greater relative quadriceps strength in the injured leg at the time of RTS after ACLR was associated with an increased risk of a second ACL injury. There was no effect of relative quadriceps strength on the risk of a second ACL injury in patients who had recovered symmetrical quadriceps strength.

**Keywords:** anterior cruciate ligament; muscle function; muscle strength; reinjury; return to sport

The results from tests of muscle function are used in clinical practice to help determine whether patients are ready to return to sport (RTS) after anterior cruciate ligament (ACL) reconstruction (ACLR). These test results are commonly reported as the limb symmetry index (LSI), which expresses the recovery of the injured knee with regard to the noninjured knee.<sup>14,29,42</sup> Passing RTS criteria are often

set when achieving an LSI of  $\geq 90\%$  in a battery of muscle function tests.<sup>16,41,42</sup>

A second ACL injury is, unfortunately, a concern after an ACLR<sup>31</sup> and can be the reason for an athlete's deciding to end one's career.<sup>25,40</sup> The collected evidence on the effect of symmetrical muscle function in a battery of tests before RTS on risk for second ACL injury is inconclusive.<sup>3,16</sup> However, patients treated with an ACLR often struggle to achieve RTS criteria in a battery of muscle function tests before RTS,<sup>42</sup> where passing rates are as low as 23% before RTS.<sup>41</sup> Despite several studies reporting differences in RTS passing

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rates,<sup>14,33,41,42</sup> as well as in the timing of RTS<sup>1-3,7,16,22,24,28,34</sup> after ACLR, there are still patients who do not recover symmetrical muscle function before RTS.<sup>41</sup>

There are concerns about the use of the LSI to evaluate muscle strength, as it only considers limb-to-limb symmetry and does not account for absolute muscle strength or absolute muscle strength normalized by body weight, that is, relative strength. It is yet to be determined whether greater relative quadriceps and hamstring strength has a protective effect on sustaining a second ACL injury. The purpose of this study was to evaluate the role of relative quadriceps and hamstring strength on the risks of (1) a second ACL injury, (2) an ACL graft rerupture, and (3) a contralateral ACL injury in patients after primary ACLR followed by RTS.

## METHODS

### Study Design

This study was performed according to the REporting of studies Conducted using Observational Routinely-collected health Data statement,<sup>5</sup> which is an extension of Strengthening the Reporting of Observational Studies in Epidemiology.<sup>39</sup> This was a prospective cohort study based on data from an observational rehabilitation outcome registry—Project ACL. The Project ACL registry, located in Gothenburg, Sweden, was begun in 2014 to improve the care of patients with ACL injuries.<sup>18</sup> Participation in Project ACL is voluntary, and patients are able to withdraw at any time. Patients are provided with written information about the project and informed consent is obtained. In Project ACL, patients are regularly assessed using validated patient-reported outcome measurements and a battery of tests for muscle function. Follow-ups are scheduled as follows: 10 weeks; 4, 8, 12, and 18 months; 2 and 5 years; and then every fifth year after ACL injury or reconstruction. Project ACL received ethics approval from the Swedish Ethical Review Authority. Patients or the public were not involved in the design, conduct, reporting, or dissemination plans of this study.

### Test Battery

The assessments in Project ACL comprise validated tests for quadriceps and hamstring strength and 3 hop tests: vertical hop, hop for distance, and 30-second side hop. The

tests of muscle function are supervised by registered physical therapists trained in standardized testing procedures. Hop testing starts at 4 months after ACLR if patients are deemed to be “ready” (have practiced a maximum hop test similar to the test procedure with their responsible physical therapist) by their responsible physical therapist. Hop tests were not used in this study.

In the present study, patients followed Project ACL test procedures and were instructed to warm up according to a standardized procedure previously published,<sup>32</sup> consisting of 10 minutes on a stationary bicycle and submaximal trials on each test. Strength testing was performed in a seated position on an isokinetic dynamometer (Biodex System 4; Biodex Medical System) at an angular speed of 90 deg/s. Three maximal trials were performed with 40 seconds of rest between each trial and the maximum torque in newton meters was recorded and registered in Project ACL. The Biodex System has an intraclass correlation coefficient of 0.95 for measuring isokinetic strength in the quadriceps and the hamstring muscle groups.<sup>11</sup>

### Patient-Reported Outcome Measures

We used the Tegner activity scale to determine RTS. The questionnaire is completed at each follow-up to assess the requirements of the knee. The Tegner is a numerical rating scale used to assess the level of knee-strenuous activity.<sup>38</sup> The physical demands gradually increase for every increased level of the Tegner scale, where the Tegner activity level 10 is defined as the most knee-strenuous activity with participation in elite-level sports (football or rugby).<sup>38</sup> The original scale ranges from 0 to 10, where a score of 0 represents being on sick leave. However, Project ACL uses a modified version of the Tegner scale that starts at level 1 (sedentary work).<sup>4</sup> RTS in this study was defined as a Tegner score  $\geq 6$  (ie, returning to knee-strenuous sport).

### Study Patients

Patients registered in Project ACL, aged 15 to 50 years with a primary ACL injury, treated with primary ACLR and rehabilitation, and with a preinjury activity level of at least 6 on the Tegner scale were eligible for inclusion. Patients who had not performed strength tests at the time of RTS or had not returned to a Tegner score  $\geq 6$  were excluded. Previous publications reported a Tegner score  $\geq 6$  as a proxy for

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athletic exposure that puts patients at risk for a second ACL injury.<sup>3</sup>

## Data Collection

Demographic characteristics and relative strength data from the test closest in time to that at which patients had returned to a Tegner score  $\geq 6$  (ie, RTS) were extracted for analysis on April 23, 2021. This means that for a patient who returned to sport at 9 months, we used test results from 8 months, whereas if a patient returned to sport at 11 months, we used the test results from 12 months. Data from strength tests of quadriceps and hamstrings were normalized by body weight in kilograms (ie, N·m/kg)<sup>19</sup> as measured at the time of testing.

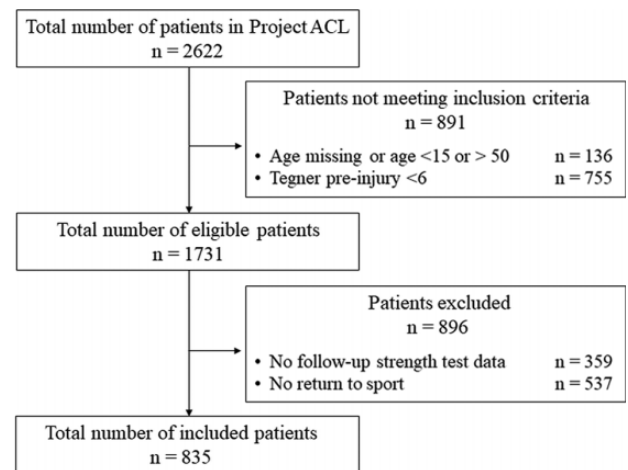
## Outcome Measures

The primary outcome was the occurrence of a second ACL injury, defined as a graft rupture of the surgically reconstructed ACL or a contralateral ACL injury. The endpoint was set as a second ACL injury or a follow-up of 2 years after RTS after ACLR. The second ACL injury was determined by a registered “new ACL injury” to a patient’s profile in Project ACL, added either by the patients themselves or the treating physical therapist. Relative strength as a risk factor for a second ACL injury was determined by analyzing the relative risk (RR) of a second ACL injury for every 1 N·m/kg increase in relative strength at the time of RTS. Patient characteristics, including sex, age at the time of ACLR, preinjury Tegner score, and time to RTS were used as confounders in a multivariable analysis, alongside relative quadriceps and hamstring strength. Secondary outcome variables were ACL graft rupture and contralateral ACL injuries.

## Statistical Analysis

Statistical analyses were performed with the SAS Statistics for Windows (Version 9.4; SAS Institute). Demographic data were recorded as mean values with standard deviations and medians with ranges. For a comparison of characteristics between sexes, the Mantel-Haenszel chi-square exact test was used for ordered categorical variables. The Fisher nonparametric permutation test was used for continuous variables.

The impact of relative strength on the occurrence of a second ACL injury was presented as the RR with 95% CI for risk estimates and *P* values. The *P* values were estimated using generalized linear models with a binomial distribution and log-link function. Univariable and multivariable analyses with confounders were used to determine the effect of relative strength on a second ACL injury. In addition, we performed sensitivity analyses using symmetry (LSI  $\geq 90\%$ ) in quadriceps or hamstring strength. The *P* value and RR are based on a continuous analysis of the original values from strength tests and their increase of 1 N·m/kg and not on stratified groups presented in Table 2 or the Supplemental Material available for this study. Cumulative incidence curves are given for the time from RTS to the second ACL injury. All of the tests were 2-sided and conducted at the 5% significance level.



**Figure 1.** Flowchart of patient inclusion and exclusion. ACL, anterior cruciate ligament; Tegner, Tegner activity scale.

## RESULTS

There were 2622 patients in Project ACL on April 23, 2021, of whom 835 patients (46% women) were included. Figure 1 presents the inclusion process.

The included patients had a mean age of  $23.9 \pm 7.7$  years and a body mass index of  $23.6 \pm 2.7$  at index ACLR. On average, patients returned to sport at  $10.2 \pm 5.5$  months after ACLR. A hamstring tendon autograft was the most commonly used autograft for ACLR (81.8%). Table 1 presents patient characteristics stratified by sex. Demographic characteristics and patient differences regarding second ACL injury are presented in Supplemental Table S1.

### Risk of a Second ACL Injury

A total of 69 (8.3%) patients reported a second ACL injury during the first 2 years after RTS. There were 47 (68%) ipsilateral ACL graft ruptures and 22 (32%) contralateral ACL injuries. Of the 69 second ACL injuries, 53 (77%) were sustained during the first year after RTS—39 (76%) ipsilateral and (3.8%) contralateral.

Figure 2 illustrates the cumulative incidence of a second ACL injury based on relative quadriceps strength for the ACL-reconstructed side. The analyses adjusted for patient sex, age at index surgery, time to RTS (months), and pre-injury Tegner score on the relative quadriceps strength of the ACL-reconstructed side resulted in a 1.69 times greater risk of a second ACL injury for every 1 N·m/kg increase in relative strength during the first 2 years after RTS (RR, 1.69 [95% CI, 1.05-2.74]; *P* = .032) (Table 2). Relative strength had no effect on the risk of a second ACL injury for either quadriceps strength on the noninjured side or hamstring strength on either side.

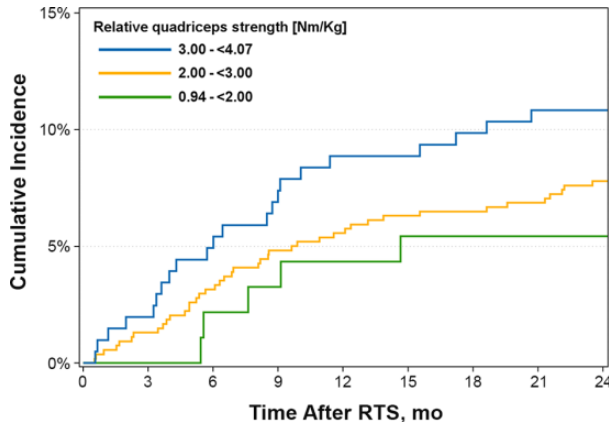
Sensitivity analyses were performed on the significant finding of a greater risk of a second ACL injury for every 1 N·m/kg increase in relative quadriceps strength on the ACL-reconstructed side (Supplemental Table S2). Relative quadriceps strength had no effect on the risk of a second

TABLE 1  
Characteristics of the Study Patients Stratified by Sex<sup>a</sup>

	Total (N = 835)	Women (n = 384)	Men (n = 451)	P <sup>b</sup>
Age at index surgery, y	23.9 ± 7.7 22.3 (15-50.4)	22 ± 7.3 19.4 (15-50.2)	25.6 ± 7.7 24.1 (15-50.4)	<.0001
Height, cm	175.4 ± 9.2 175 (150-200)	168.3 ± 6.3 169 (150-186)	181.5 ± 6.5 182 (162-200)	<.0001
Weight, kg	73.1 ± 12.4 72 (47-118)	64.5 ± 8.3 64 (47-92)	80.4 ± 10.4 80 (53-118)	<.0001
BMI	23.6 ± 2.7 23.4 (17.3-34.8)	22.7 ± 2.4 22.6 (17.3-32.7)	24.4 ± 2.7 24.4 (17.5-34.8)	<.0001
Time to RTS, mo	10.2 ± 5.5 8.5 (1.7-24.7)	11.1 ± 5.5 11.8 (2.1-24.7)	9.50 ± 5.37 8.11 (1.71-24.57)	<.0001
Graft type				.98
Hamstring tendon autograft	672 (81.8)	309 (82)	363 (81.6)	
Patellar tendon autograft	138 (16.8)	63 (16.7)	75 (16.9)	
Other tendon autograft	12 (1.5)	5 (1.3)	7 (1.6)	
Preinjury Tegner score				.41
6	58 (6.9)	26 (6.8)	32 (7.1)	
7	134 (16)	54 (14.1)	80 (17.7)	
8	214 (25.6)	124 (32.3)	90 (20)	
9	268 (32.1)	112 (29.2)	156 (34.6)	
10	161 (19.3)	68 (17.7)	93 (20.6)	

<sup>a</sup>Data are presented as n (%) for categorical variables and as mean ± SD and median (range) for continuous variables. Bold P values indicate statistically significant differences between groups ( $P < .05$ ). BMI, body mass index; RTS, return to sport.

<sup>b</sup>The Mantel-Haenszel chi-square exact test was used for ordered categorical variables, the chi-square exact test was used for nonordered categorical variables, and the Fisher nonparametric permutation test was used for continuous variables.



**Figure 2.** Cumulative incidence of a second ACL injury after RTS, stratified by relative quadriceps strength on the ACL reconstructed side. ACL, anterior cruciate ligament; RTS, return to sport.

ACL injury when accounting for symmetrical quadriceps strength (1.33 [95% CI, 0.69-2.56];  $P = 0.39$ ).

#### Risk of ACL Graft Rupture and Contralateral ACL Injury

Increased relative quadriceps or hamstring strength had no effect on the risk of ACL graft rupture or contralateral ACL injury after RTS in patients after a primary ACLR (Supplemental Tables S3 and S4). A multivariable analysis was not

possible to perform because of the small number of contralateral ACL injuries. Figure 3 presents the cumulative incidence of ipsilateral graft rupture and contralateral ACL injury.

#### DISCUSSION

The main finding in this study was an increased risk of a second ACL injury with every 1 N·m/kg increase in relative quadriceps strength on the ACL-reconstructed side when accounting for differences in patient age, sex, preinjury activity level, and time to RTS. However, when adjusting for symmetrical quadriceps strength, there was no effect of relative quadriceps strength on the risk of a second ACL injury. This supports the importance of recovery of both preoperative absolute muscle strength and LSI to minimize the risk of second injury in patients before RTS after ACLR. In addition, increased relative quadriceps or hamstring strength had no effect on a second ACL injury on the ipsilateral or contralateral knee alone.

#### Risk of a Second ACL Injury

The study findings indicated that for every 1 N·m/kg increase in relative quadriceps strength on the ACL-reconstructed side, the risk of a second ACL injury increased 1.69 times when accounting for patient characteristics and time of RTS, which adds a new perspective to the complexity of a second ACL injury. Although the exact mechanisms behind our results cannot be determined by

TABLE 2  
Relative Risk of Second ACL Injury for Every 1 N·m/kg Increase in Relative Strength<sup>a</sup>

Distribution of Relative Strength, N·m/kg	Second ACL injury, n (%)	Univariable <sup>b</sup>		Adjusted <sup>c</sup>	
		RR (95% CI) Second ACL Injury ≤2 y After RTS	P	RR (95% CI) Second ACL Injury ≤2 y after RTS	P
Injured side, quadriceps (n = 835)		1.43 (0.93-2.21)	.11	1.69 (1.05-2.74)	<b>.032</b>
0.94 to <2	5 (5.4)				
2 to <2.50	18 (7.2)				
2.50 to <3	24 (8.3)				
3 to <3.50	17 (10.1)				
3.50 to 4.07	5 (14.7)				
Injured side, hamstring (n = 833)		0.91 (0.44-1.88)	.79	0.95 (0.43-2.09)	.90
0.33 to <1.20	12 (9)				
1.20 to <1.40	19 (10.6)				
1.40 to <1.60	13 (6)				
1.60 to <1.80	14 (8.6)				
1.80 to 2.51	11 (7.9)				
Uninjured side, quadriceps (n = 834)		1.10 (0.65-1.87)	.71	1.14 (0.63-2.05)	.67
1.47 to <2.01	1 (3.7)				
2.01 to <2.50	15 (10.6)				
2.50 to <3	28 (7.8)				
3 to <3.50	20 (8)				
3.50 to 4.26	5 (9.3)				
Uninjured side, hamstring (n = 832)		0.67 (0.31-1.49)	.33	0.64 (0.26-1.63)	.35
0.71 to <1.20	10 (10.5)				
1.20 to <1.40	15 (9.3)				
1.40 to <1.60	20 (9.3)				
1.60 to <1.80	13 (6.5)				
1.80 to 2.77	11 (6.8)				

<sup>a</sup>P values and RR are based on original values and not on stratified groups. The Bold P value indicates statistical significance (P < .05). ACL, anterior cruciate ligament; RR, relative risk; RTS, return to sport.

<sup>b</sup>All tests were performed with univariable generalized linear models.

<sup>c</sup>Adjusting for patient sex, age at index surgery, time to RTS (months), and preinjury Tegner score using a generalized linear model.

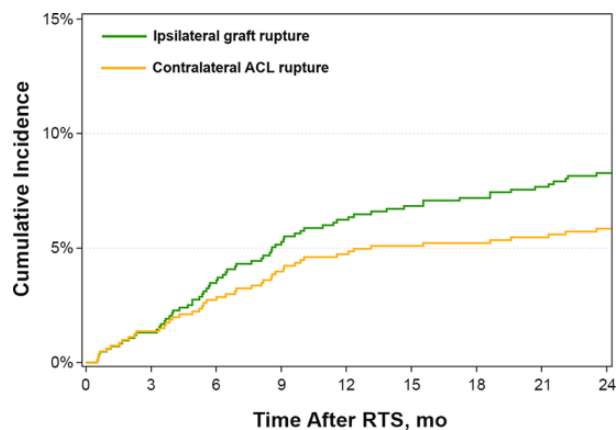


Figure 3. Cumulative incidence of ipsilateral graft rupture and contralateral ACL rupture after RTS. ACL, anterior cruciate ligament; RTS, return to sport.

this study, our results indicate that the stronger the patients' quadriceps on the ACL-reconstructed side are, normalized by body weight, the greater the risk of a second ACL injury. During sports, when athletes contract their

quadriceps muscle, an anterior translation of the tibia is induced, which imposes a strain on the ACL.<sup>17</sup> Sagittal plane control has recently been shown to play an important role during sporting tasks where limited impact absorption through the hip and trunk and a more asymmetrical center of mass through the knee in the sagittal plane can increase loading through the knee.<sup>8,20,21</sup> Our results may be explained by the patients' being able to expose their knees to greater forces without being fully recovered, that is, not being able to handle the induced excessive strain on their ACLs. This is supported by the fact that relative quadriceps strength in patients with a symmetrical quadriceps strength had no effect on second ACL injury, suggesting that these patients may be better prepared for RTS or have a better capacity in the reconstructed knee to cope with the forces during sports participation. In addition, no significant effect was found for hamstrings strength on the risk of a second ACL injury. As the hamstrings are believed to play a role in rotatory stability and act to limit excessive tibial anterior translation,<sup>36</sup> a reduced absolute hamstring strength relative to body weight may influence the risk for second ACL injuries. However, no effect was found in our results.

Although there is conflicting evidence on the effectiveness of RTS testing,<sup>26</sup> the current proposed RTS criteria<sup>14,16</sup> are based on limb-to-limb symmetry, that is, achieving an LSI  $\geq 90\%$  to be defined as ready to RTS,<sup>27</sup> which is believed to have a protective effect on the risk of sustaining a second ACL injury. In contrast, Bodkin et al<sup>6</sup> presented results suggesting an increased risk for a second ACL injury with 2.1% for every 1% increase in quadriceps strength symmetry at 6 months for patients who return to activity  $< 8$  months after ACLR. Our sensitivity analysis showed that our finding of increased risk for second ACL injury was no longer present in patients who had symmetrical strength. One concern about recovering symmetry after ACLR is whether it is achieved by a strength decrease in the nonreconstructed leg, thereby masking bilateral weakness.<sup>42</sup> However, when interpreting our results, the recovery of symmetrical quadriceps strength after ACLR appears to eliminate the association between increased quadriceps strength and risk for a second ACL injury. In addition, we acknowledge that strength deficits have been associated with more severe knee-related symptoms,<sup>10,35,44</sup> which suggests that encouraging patients to increase their strength as part of recovering symmetrical function is advised.

### Risk of ACL Graft Rupture and Contralateral ACL Injury

The overall rate of a second ACL injury in the present study appears to be lower compared with a previous study—8% versus 15% to 25%.<sup>30</sup> Previous results from a systematic review showed a greater rate of contralateral injuries as second ACL injuries, 12% contralateral versus 8% ipsilateral ACL injuries, during a 51-month follow-up after ACLR.<sup>43</sup> Our findings suggest a greater rate of ipsilateral graft rupture as a second ACL injury, 6% ipsilateral versus 3.8% contralateral, during the first 2 years after RTS following ACLR. The difference in ipsilateral graft rupture or contralateral injury as a second ACL injury may be due to different periods of follow-up, 24 months after RTS in our study versus 51 months after ACLR in the systematic review,<sup>43</sup> as other researchers have suggested that ipsilateral graft ruptures are more common during the first 2 years after RTS following ACL reconstruction.<sup>9</sup>

Our results revealed no significant effect of relative quadriceps or hamstring strength on the risk of either an ACL graft rupture or a contralateral second ACL injury when analyzed separately 2 years after RTS following ACLR. Future studies on risk factors for ipsilateral and contralateral secondary ACL injuries separately are therefore warranted; however, this requires a larger cohort of patients sustaining a second ACL injury. The present study was underpowered to perform multivariable analyses for contralateral second ACL injury.

### Strengths and Limitations

In this study, we analyzed the risk of a second ACL injury in patients after primary ACLR. The use of a rehabilitation registry provided a large cohort of 835 patients who

underwent ACLR, increasing generalizability to the population of patients returning to a physical activity level corresponding to a Tegner score  $\geq 6$  after ACLR and enabling sensitivity analyses with known confounders. Although we had a large number of eligible patients for inclusion, a considerable number of patients were excluded, as they had not returned to sport or had not attended the follow-ups in Project ACL.

The definition of RTS used in our study was a Tegner score  $\geq 6$ , which means that some patients may not have returned to their preinjury level of activity or may have returned to sport in the early stage of rehabilitation. As the Tegner is self-reported, patients in our cohort who had a preinjury activity level  $\geq 6$  may have returned to a more knee-strenuous activity than other patients and were therefore exposed to a greater risk of a second ACL injury. It is also worth mentioning that there were no patients in our cohort who sustained a second ACL injury before returning to Tegner activity level 6. In addition, the Tegner score accounts for neither time of exposure nor the intensity of physical activity, which are known to influence the risk of a second ACL injury,<sup>15</sup> especially if the increase in load/exposure exceeds the patient's knee capacity.<sup>12,13</sup> This is especially important considering the greater rate of a second ACL injury that occurred during the first year after RTS compared with the second year. Furthermore, the test analyzed in this study was the test closest in time to RTS, which means that there may be a difference in time between RTS and time of testing between patients, and quadriceps strength may also differ because of this time gap, which could have led to an over- or underestimation of quadriceps strength at the time of RTS.

Since the reasons for a second ACL injury are multifactorial, we acknowledge that there might be other measurements of muscle function and surgical techniques<sup>37</sup> that could help explain the risk of a second ACL injury<sup>23</sup> that were not accounted for in this study. To account for the risk of type 1 error, we presented confidence intervals for every analysis.

### CONCLUSION

Greater quadriceps strength in the injured leg at the time of RTS after ACLR was associated with an increased risk of a second ACL injury. In patients who had recovered symmetrical quadriceps strength, there was no effect of relative quadriceps strength on the risk of a second ACL injury.

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## REFERENCES

1. Ardern CL, Taylor NF, Feller JA, Whitehead TS, Webster KE. Psychological responses matter in returning to preinjury level of sport after anterior cruciate ligament reconstruction surgery. *Am J Sports Med.* 2013;41(7):1549-1558.
2. Ardern CL, Webster KE, Taylor NF, Feller JA. Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play. *Br J Sports Med.* 2011;45(7):596-606.
3. Beischer S, Gustavsson L, Senorski EH, et al. Young athletes who return to sport before 9 months after anterior cruciate ligament reconstruction have a rate of new injury 7 times that of those who delay return. *J Orthop Sports Phys Ther.* 2020;50(2):83-90.
4. Beischer S, Hamrin Senorski E, Thomeé P, Thomeé R. Validation of an 18-item version of the Swedish Knee Self-Efficacy Scale for patients after ACL injury and ACL reconstruction. *J Exp Orthop.* 2021;8(1):96.
5. Benchimol EI, Smeeth L, Guttman A, et al. The REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) statement. *PLoS Med.* 2015;12(10):e1001885.
6. Bodkin SG, Hertel J, Diduch DR, et al. Predicting anterior cruciate ligament reinjury from return-to-activity assessments at 6 months postsurgery: a prospective cohort study. *J Athl Train.* 2022;57(4):325-333.
7. Creighton DW, Shrier I, Shultz R, Meeuwisse WH, Matheson GO. Return-to-play in sport: a decision-based model. *Clin J Sport Med.* 2010;20(5):379-385.
8. Della Villa F, Buckthorpe M, Grassi A, et al. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *Br J Sports Med.* 2020;54(23):1423-1432.
9. Della Villa F, Häggglund M, Della Villa S, Ekstrand J, Waldén M. High rate of second ACL injury following ACL reconstruction in male professional footballers: an updated longitudinal analysis from 118 players in the UEFA Elite Club Injury Study. *Br J Sports Med.* 2021;55(23):1350-1356.
10. Eitzen I, Grindem H, Nilstad A, Moksnes H, Risberg MA. Quantifying quadriceps muscle strength in patients with ACL injury, focal cartilage lesions, and degenerative meniscus tears: differences and clinical implications. *Orthop J Sports Med.* 2016;4(10):2325967116667717.
11. Feiring DC, Ellenbecker TS, Derscheid GL. Test-retest reliability of the Biodex isokinetic dynamometer. *J Orthop Sports Phys Ther.* 1990;11(7):298-300.
12. Gabbett TJ. How much? How fast? How soon? Three simple concepts for progressing training loads to minimize injury risk and enhance performance. *J Orthop Sports Phys Ther.* 2020;50(10):570-573.
13. Gabbett TJ. The training-injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med.* 2016;50(5):273-280.
14. Gokeler A, Welling W, Benjamin A, Lemmink K, Seil R, Zaffagnini S. A critical analysis of limb symmetry indices of hop tests in athletes after anterior cruciate ligament reconstruction: a case control study. *Orthop Traumatol Surg Res.* 2017;103(6):947-951.
15. Grassi A, Macchiarella L, Filippini M, Lucidi GA, Della Villa F, Zaffagnini S. Epidemiology of anterior cruciate ligament injury in Italian first division soccer players. *Sports Health.* 2020;12(3):279-288.
16. Grindem H, Snyder-Mackler L, Moksnes H, Engebretsen L, Risberg MA. Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: the Delaware-Oslo ACL cohort study. *Br J Sports Med.* 2016;50(13):804.
17. Gross MT, Tyson AD, Burns CB. Effect of knee angle and ligament insufficiency on anterior tibial translation during quadriceps muscle contraction: a preliminary report. *J Orthop Sports Phys Ther.* 1993;17(3):133-143.
18. Hamrin Senorski E, Samuelsson K, Thomeé C, Beischer S, Karlsson J, Thomeé R. Return to knee-strenuous sport after anterior cruciate ligament reconstruction: a report from a rehabilitation outcome registry of patient characteristics. *Knee Surg Sports Traumatol Arthrosc.* 2017;25(5):1364-1374.
19. Harbo T, Brincks J, Andersen H. Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects. *Eur J Appl Physiol.* 2012;112(1):267-275.
20. King E, Richter C, Daniels KAJ, et al. Biomechanical but not strength or performance measures differentiate male athletes who experience ACL reinjury on return to level 1 sports. *Am J Sports Med.* 2021;49(4):918-927.
21. King E, Richter C, Daniels KAJ, et al. Can biomechanical testing after anterior cruciate ligament reconstruction identify athletes at risk for subsequent ACL injury to the contralateral uninjured limb? *Am J Sports Med.* 2021;49(3):609-619.
22. Kvist J, Ek A, Sporrstedt K, Good L. Fear of re-injury: a hindrance for returning to sports after anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2005;13(5):393-397.
23. Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. *Br J Sports Med.* 2016;50(15):946-951.
24. Lai CCH, Ardern CL, Feller JA, Webster KE. Eighty-three per cent of elite athletes return to preinjury sport after anterior cruciate ligament reconstruction: a systematic review with meta-analysis of return to sport rates, graft rupture rates and performance outcomes. *Br J Sports Med.* 2018;52(2):128.
25. Lai CCH, Feller JA, Webster KE. Fifteen-year audit of anterior cruciate ligament reconstructions in the Australian Football League from 1999 to 2013: return to play and subsequent ACL injury. *Am J Sports Med.* 2018;46(14):3353-3360.
26. Losciale JM, Zdeb RM, Ledbetter L, Reiman MP, Sell TC. The association between passing return-to-sport criteria and second anterior cruciate ligament injury risk: a systematic review with meta-analysis. *J Orthop Sports Phys Ther.* 2019;49(2):43-54.
27. Lynch AD, Logerstedt DS, Grindem H, et al. Consensus criteria for defining "successful outcome" after ACL injury and reconstruction: a Delaware-Oslo ACL cohort investigation. *Br J Sports Med.* 2015;49(5):335-342.
28. Muller B, Yabroudi MA, Lynch A, et al. Return to preinjury sports after anterior cruciate ligament reconstruction is predicted by five independent factors. *Knee Surg Sports Traumatol Arthrosc.* 2022;30(1):84-92.
29. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19(5):513-518.
30. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. *Clin J Sport Med.* 2012;22(2):116-121.
31. Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of second ACL injuries 2 years after primary ACL reconstruction and return to sport. *Am J Sports Med.* 2014;42(7):1567-1573.
32. Piussi R, Beischer S, Thomeé R, Hamrin Senorski E. Superior knee self-efficacy and quality of life throughout the first year in patients who recover symmetrical muscle function after ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc.* 2020;28(2):555-567.
33. Piussi R, Broman D, Musslinger E, Beischer S, Thomeé R, Hamrin Senorski E. Recovery of preoperative absolute knee extension and flexion strength after ACL reconstruction. *BMC Sports Sci Med Rehabil.* 2020;12(1):77.
34. Shelbourne KD, Benner RW, Gray T. Return to sports and subsequent ACL injury rates after revision ACL reconstruction with patellar tendon autograft. *Orthop J Sports Med.* 2013;1(suppl 4):2325967113S2325900003.
35. Sherman D, Birchmeier T, Kuenze CM, et al. Thigh-muscle and patient-reported function early after anterior cruciate ligament reconstruction: clinical cutoffs unique to graft type and age. *J Athl Train.* 2020;55(8):826-833.
36. Solomonow M, Baratta R, Zhou BH, et al. The synergistic action of the anterior cruciate ligament and thigh muscles in maintaining joint stability. *Am J Sports Med.* 1987;15(3):207-213.

37. Svantesson E, Hamrin Senorski E, Baldari A, et al. Factors associated with additional anterior cruciate ligament reconstruction and register comparison: a systematic review on the Scandinavian knee ligament registers. *Br J Sports Med.* 2019;53(7):418-425.
38. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop Relat Res.* 1985;198:43-49.
39. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. The Strengthening of Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol.* 2008;61(4):344-349.
40. Waldén M, Häggglund M, Magnusson H, Ekstrand J. ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *Br J Sports Med.* 2016;50(12):744-750.
41. Webster KE, Hewett TE. What is the evidence for and validity of return-to-sport testing after anterior cruciate ligament reconstruction surgery? A systematic review and meta-analysis. *Sports Med.* 2019;49(6):917-929.
42. Wellsandt E, Failla MJ, Snyder-Mackler L. Limb symmetry indexes can overestimate knee function after anterior cruciate ligament injury. *J Orthop Sports Phys Ther.* 2017;47(5):334-338.
43. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. Risk of secondary injury in younger athletes after anterior cruciate ligament reconstruction: a systematic review and meta-analysis. *Am J Sports Med.* 2016;44(7):1861-1876.
44. Zwolski C, Schmitt LC, Quatman-Yates C, Thomas S, Hewett TE, Paterno MV. The influence of quadriceps strength asymmetry on patient-reported function at time of return to sport after anterior cruciate ligament reconstruction. *Am J Sports Med.* 2015;43(9):2242-2249.