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メタデータ	言語: English 出版者: 公開日: 2025-06-11 キーワード (Ja): キーワード (En): 作成者: 仙石 拓也, 中瀬 順介, 水野 雄伸, 石田 善浩, Yusuke Yanatori, 竹本 直起, 出村 諭 メールアドレス: 所属:
URL	https://doi.org/10.24517/0002002903

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Received: 16 January 2024 | Accepted: 1 July 2024

DOI: 10.1002/ksa.12370

Knee Surgery, Sports Traumatology, Arthroscopy WILEY

Knee flexor strength at 6 months after anterior cruciate ligament reconstruction using hamstring tendon can be predicted from that at 3 months

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Abstract

Purpose: This study aimed to identify factors influencing persistent muscle weakness in knee flexor strength after anterior cruciate ligament (ACL) reconstruction using the hamstring tendon and establish a clear cut-off value at 3 months postoperatively for the limb symmetry index (LSI) to exceed 90% at 6 months postoperatively.

Methods: One hundred forty-eight patients undergoing ACL reconstruction were included and categorised into two groups based on knee flexor strength at 6 months postoperatively: patients with LSI of 90% or greater (achieved group: $n = 114$) and patients with LSI less than 85% (nonachieved group: $n = 34$). Items with significant differences between the two groups (preoperative waiting period, LSI to body weight ratio of knee flexor and extensor strength at 3 months postoperatively and peak torque angle of knee flexor muscle) were included in the multiple logistic regression analysis. Additionally, a receiver operating characteristic curve was used to calculate the cut-off value of the LSI at 3 months postoperatively, which was required to achieve the LSI criteria for knee flexor strength 6 months postoperatively.

Results: Multiple logistic regression analysis extracted the preoperative waiting period and LSI for knee flexor strength at 3 months postoperatively. The cut-off value at 3 months postoperatively was 76.9% (area under the curve value, 0.82; sensitivity, 0.76; and specificity, 0.81) of the LSI.

Conclusion: The LSI of at least 76.9% for knee flexor strength at 3 months after ACL reconstruction was an indicator for achieving the 6 months postoperatively. This is a criterion to aim for, considering the stress on the graft and the regeneration process of the semitendinosus tendon.

Level of evidence: Level III.

KEYWORDS

anterior cruciate ligament reconstruction, cut-off value, knee flexor strength, limb symmetry index, preoperative waiting period

Abbreviations: ACL, anterior cruciate ligament; AUC, area under the curve; BW, body weight; HT, hamstring tendon; LSI, limb symmetry index; ROM, range of motion; ST, semitendinosus tendon.

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INTRODUCTION

The recovery of lower extremity muscle strength after anterior cruciate ligament (ACL) reconstruction determines the turning point for patients, including when to start running and return to sports [13, 26]. Numerous studies have been conducted on lower limb muscle strength after ACL reconstruction, primarily focussing on knee extensor strength [14, 31, 32, 38] and more recently on knee flexor strength [30, 42], although it remains insufficient.

ACL reconstruction frequently uses the semitendinosus tendon (ST), a hamstring component, as the autograft. This procedure is associated with postoperative loss of knee flexor strength [6, 12, 28] and muscle hypotrophy [11, 17]. Cristiani et al [6]. reported a limb symmetry index (LSI) of 85% for knee flexor strength at 6 months after ACL reconstruction using ST, with an average of <90% at 2 years postoperatively. Additionally, if the ST alone does not provide sufficient graft thickness, the gracilis tendon is also harvested, potentially leading to further weakening of the knee flexor strength [9, 30]. Tissue regeneration of ST muscle mass and tendon harvesting sites, as observed in imaging MRI studies, can take more than 6 months after harvesting [33, 34], significantly impacting rehabilitation to improve knee flexor strength.

The hamstrings and soleus muscles attach posteriorly to the tibia, generating posterior shear forces at 20°–30° of knee flexion or greater, reducing the load on the ACL and enhancing knee stability [21, 22]. Cadaveric studies have reported that ST helps prevent the knee valgus [7, 40] and lower leg external rotation [36], both contributing factors to ACL injury. Kyristisr et al. [19] reported a 10.6-fold increase in ACL reinjury risk with a 10% decrease in the hamstring-to-quadriceps ratio among professional soccer players, indicating significant risk associated with knee flexor weakness.

While there has been a gradual increase in studies focussing on the importance of improving knee flexor strength after ACL reconstruction [4], the factors contributing to decreased knee flexor strength have not been examined in detail, indicating a need for clinically useful information beyond the use of hamstring tendon (HT) in the graft. This study aimed to identify factors influencing persistent muscle weakness 6 months after ACL reconstruction using HT and to establish a clear cut-off value at 3 months postoperatively for the LSI to exceed 90% at 6 months. No prior studies have provided a clear cut-off value for obtaining sufficient knee flexor strength after ACL reconstruction, making this study of high clinical significance and novelty. It was hypothesised that knee flexor strength during the preoperative waiting period and at 3 months postoperatively would be related to knee flexor strength at 6 months postoperatively.

MATERIALS AND METHODS

This study was approved by the medical ethics review committee of Kanazawa University (Approval No: 2015-058 1860). Informed consent was obtained from all participants.

This retrospective study included 208 patients who underwent ACL reconstruction with HT between 2015 and 2023. The inclusion criteria were as follows: primary ACL reconstruction using the HT autograft, a preoperative Tegner activity score of 6 or higher and postoperative follow-up at our hospital. The exclusion criteria were lack of muscle strength measurement data at 3 or 6 months postoperatively and an LSI between 85% and 90%. In accordance with inclusion and exclusion criteria, 148 patients (72 males and 76 females; average age ± standard deviation: 22.2 ± 10.3 years) were selected (Figure 1). All patients were discharged without any postoperative complications.

Procedure for muscle strength measurement and grouping

Muscle strength was measured using an isokinetic dynamometer (BIODEX System 4; BIODEX Company) at 3 and 6 months after ACL reconstruction. The detailed settings for the measurements were those that had been used in a previous study [39]. The measurements were performed at an angular velocity of 60°/s of concentric contraction. Gravity correction of the lower leg was also performed to obtain accurate knee flexor strength with a measurement range of 0°–100°. Three sets of three reps were performed, two as practice sets and the third as maximal for data extraction. The LSI and body weight (BW) ratios were calculated based on peak torque. The formulas for the values were as follows: LSI = involved limb strength (peak torque)/noninvolved limb strength (peak torque) ×100 and BW ratio = each peak torque/BW.

In this study, the patients were categorised into two groups according to the LSI of knee flexor strength at 6 months. Grouping was performed in accordance with that of a previous study [29], with LSI ≥ 90% defined as 'achieved group' and LSI < 85% defined as a 'non-achieved group'.

Surgical technique and rehabilitation protocol

All patients underwent anatomical single-bundle ACL reconstruction with HT [23], and if the cross-sectional area of the ST alone was less than $6 \times 10\,mm^2$, an additional gracilis tendon was harvested [20]. All surgeries were performed by the same orthopaedic surgeon.

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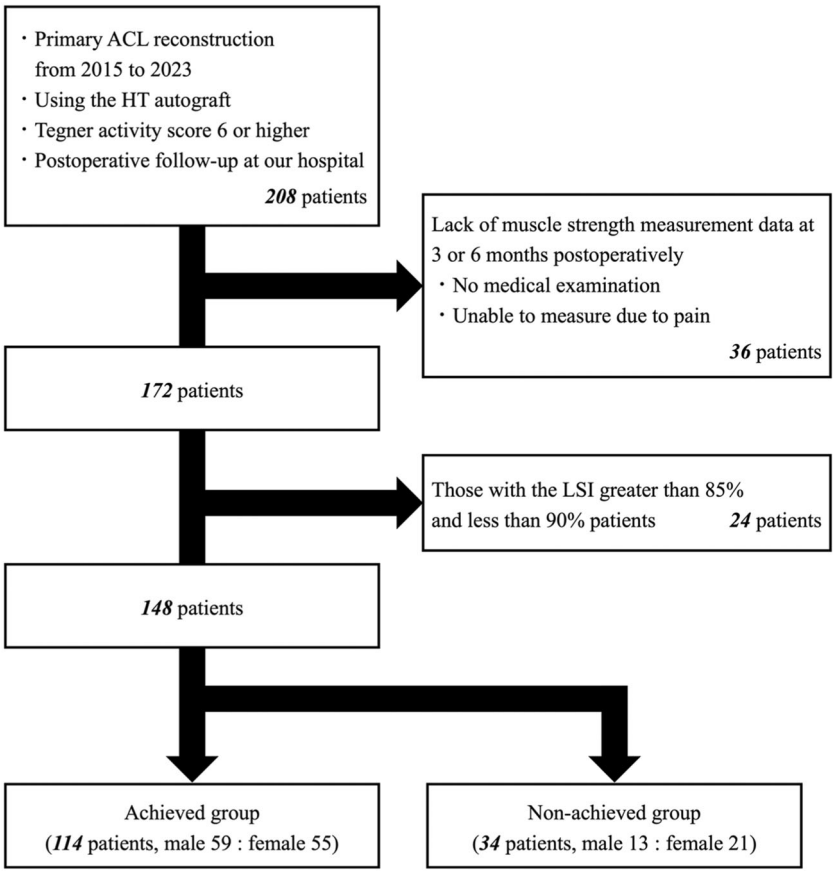

FIGURE 1 Flowchart of patient recruitment in this study. In total, 208 patients met the inclusion criteria. Sixty patients were excluded based on the exclusion criteria. Finally, 148 patients were included in the study and categorised into 114 patients with an LSI of 90% or greater in knee flexor strength (achieved group) and 34 patients with an LSI of less than 85% (nonachieved group). Among those excluded, 24 (11.5%) were owing to the study design and 36 (17.3%) for other reasons. ACL, anterior cruciate ligament; HT, hamstring tendon; LSI, limb symmetry index.

Rehabilitation after ACL reconstruction was similar to that reported previously [30]. The same protocol was used for all patients. Rehabilitation was initiated at the first visit after the ACL injury. Preoperatively, the priority was to improve swelling and range of motion (ROM; 0°–125°). Once these improvements were achieved, resistance training, such as squatting, was started while wearing a knee brace. Leg curls were also permitted in the mechanical training. Postoperative rehabilitation began the day after surgery with joint contraction of the quadriceps and hamstring muscles, ROM exercises and full weight bearing in the knee joint extension position. Several goals have been set for rehabilitation progression and implemented in stages. First, the goal was to achieve an ROM of 0°–90° by 2 weeks and 0°–120° by 4 weeks postoperatively. At 4 weeks postoperatively, if the target ROM was achieved and swelling and pain were not noticeable, squats and front lunges were introduced to strengthen the lower limb muscles. Second, at 3 months postoperatively, isokinetic muscle strength measurements indicated that patients were allowed to begin running if their knee extensor and flexor strengths were at least 60% of the LSI [8]. Third, a similar muscle strength test performed 6 months postoperatively allowed participation in sports activities if the LSI was 90% or higher. Thereafter, rehabilitation shifted to a programme that incorporated more sports-specific movements.

Exercises aimed at strengthening the hamstrings and the timing of their initiation are summarised in Table 1. In addition, squats, lunge movements (front, side and Y), Bulgarian squats and star excursions, which were incorporated as one of the objectives to strengthen the hamstrings, were performed with a double flexion strategy [4] (Figure 2).

Assessment variables

Several parameters were assessed. The evaluation items were basic information (age, sex, height, weight, body mass index, preoperative waiting period, preoperative Tegner activity score, graft type, meniscus injury [Yes or No] and cartilage injury [Yes or No]), knee ROM (preoperative limited knee extension [Yes or No], preoperative hyperextended knee [Yes or No],

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hyperextended knee at 3 months [Yes or No]) and knee muscle strength (LSI and BW ratio of knee extensor and flexor at 3 months, time to peak torque of knee extensor and flexor at 3 months, peak torque angle of knee extensor and flexor at 3 months, acceleration time of knee extensor and flexor at 3 months and hamstrings to quadriceps ratio at 3 months).

The graft type was defined as ST only or ST with gracilis tendon. Range of motion of the knee joint was evaluated in 5° increments with a commonly used goniometer. Limited knee extension was defined as a flexion >5°. Knee hyperextension was defined as an extension of >5°. Muscle strength measurements with an isokinetic dynamometer were also evaluated for measurement reproducibility. The results showed that the intraclass correlation coefficient (1, 2) was 0.99, indicating excellent reliability.

TABLE 1 Exercise programme to strengthen hamstrings.

Prehabilitation	Squat, knee lunge (front, side, Y), leg curl
Day 1	Quadriceps and hamstrings cocontraction
2 weeks	Isometric hamstring exercise
4 weeks	Half squat, front knee lunge
6 weeks	Bulgarian squat, side and Y lunge
8 weeks	Single leg squat
10 weeks	Star excursion, low walk with tube, plyometric jump
12 weeks	Leg curl

Note: These programmes are designed to improve hamstring strength. The close kinetic chain exercise focussed on teaching postural control, promoting hamstring contraction and reducing traction stress on the anterior cruciate ligament.

Statistical analysis

The analysis in this study was conducted with reference to a previous study [37]. All analyses were performed using the JMP ver. 14 software (SAS Institute). First, univariate analyses were performed on the achieved and nonachieved groups to extract factors affecting knee flexor strength at 6 months postoperatively. In the univariate analysis, normality was confirmed using the Shapiro–Wilk test, followed by the Student's t test, Wilcoxon test and Pearson's χ^2 test, depending on the results. Second, multiple logistic regression analysis was performed to investigate the factors influencing knee flexor strength at 6 months postoperatively, with the LSI of knee flexor strength as the dependent variable and variables that showed statistically significant differences in the univariate analysis as independent variables. Finally, receiver operating characteristic curves were used to calculate the cut-off value of knee flexor strength at 3 months postoperatively required to achieve LSI ≥ 90% at 6 months postoperatively.

G* Power 3.1.9.7 (Franz Paul) was used to determine the power of this study. A priori power analysis was used to calculate the sample size for the univariate analysis, and the following results were obtained: 142 patients were needed based on effect size (d) of 0.50, an α level of 0.05 and a power of 0.80. In addition, a priori power was used to calculate the

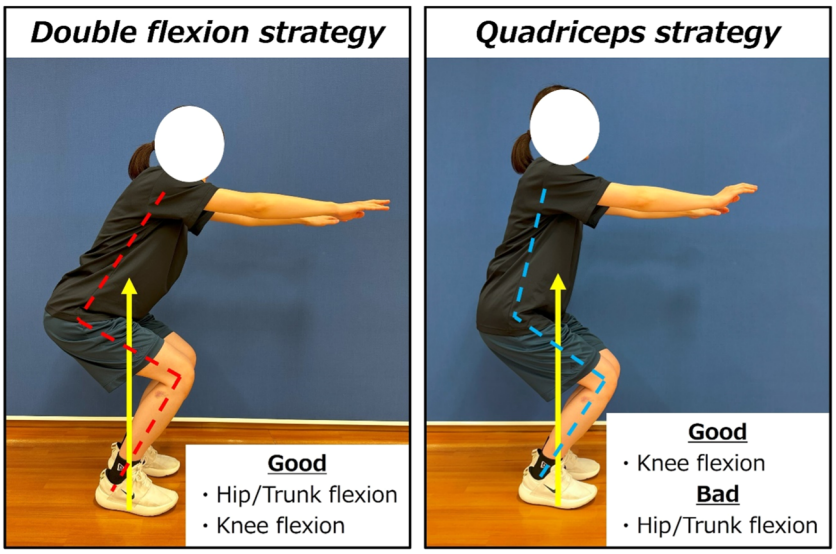

FIGURE 2 Strategies for performing squat and lunge movements. This figure is based on the report of Buckthorpe et al. [4]. Double flexion strategy: It is a balanced movement strategy with sufficient flexion of the trunk, hip and knee joints and is the ideal movement posture. Quadriceps strategy: Knee flexion is equivalent to double flexion strategy, but trunk and hip flexion are inadequate, and the movement strategy relies on the quadriceps muscles.

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sample size for the multiple regression logistic analysis, and the following results were obtained: 146 patients were needed based on an effect size (f^2) of 0.15, an α level of 0.05, a power of 0.95 and several predictors of 6.

RESULTS

Based on the LSI results of knee flexor strength at 6 months postoperatively, 114 patients were categorised into the achieved group and 34 into the nonachieved group (Figure 1).

Univariate analysis showed statistically significant differences (Table 2) in the preoperative waiting period, LSI and BW ratio of knee extensor and flexor strength at 3 months and peak torque angle of knee flexors at 3 months postoperatively. Furthermore, two items were extracted from the multiple logistic regression analysis (Table 3): preoperative waiting period (OR: 1.01, 95% CI: 1.001–1.02, $p = 0.04$) and LSI of the knee flexors at 3 months (OR: 0.92, 95% CI: 0.87–0.96, $p < 0.01$).

Finally, the 3 months postoperative cut-off value for achieving LSI ≧ 90% of knee flexor strength at 6 months postoperatively was 76.9% of the LSI. Ninety-seven patients (65.5%) achieved the LSI criterion value

TABLE 2 Comparison between the achieved group and the nonachieved group.

	Achieved group ($n = 114$)	Nonachieved group ($n = 34$)	p Value
Basic information			
Age (years)	20.5 ± 8.7 (12–60)	22.6 ± 10.9 (13–48)	n.s.
Sex (male: female)	59:55	13:21	n.s.
Height (m)	1.7 ± 0.9 (1.5–1.8)	1.6 ± 0.8 (1.4–1.8)	n.s.
Weight (kg)	62.4 ± 11.2 (39.7–120.0)	62.4 ± 14.2 (35.0–118.0)	n.s.
BMI (kg/m^2)	22.6 ± 2.8 (17.2–36.9)	23.1 ± 4.0 (16.9–38.7)	n.s.
Preoperative waiting period (days)	59.8 ± 39.6 (9–215)	79.6 ± 57.4 (12–267)	0.045
Preoperative Tegner activity score	8 (6–9)	8 (6–9)	n.s.
Graft (ST: STG)	52:62	17:17	n.s.
Meniscus injury (yes)	74 (%)	26 (%)	n.s.
Cartilage injury (yes)	28 (%)	11 (%)	n.s.
Knee range of motion			
Preoperative limited knee extension (yes)	6 (%)	3 (%)	n.s.
Preoperative hyperextended knee (yes)	21 (%)	11 (%)	n.s.
3 M hyperextended knee (yes)	16 (%)	7 (%)	n.s.
Knee muscle strength			
3 M knee extensor LSI (%)	79.6 ± 17.5 (36.0–137.3)	66.0 ± 17.7 (23.9–100.8)	<0.01
3 M knee flexor LSI (%)	92.0 ± 20.1 (52.8–169.7)	70.3 ± 14.5 (36.2–106.8)	<0.01
3 M knee extensor BW ratio (N/kg)	1.7 ± 0.6 (0.8–3.7)	1.5 ± 0.6 (0.6–3.2)	0.02
3 M knee flexor BW ratio (N/kg)	0.9 ± 0.3 (0.3–1.9)	0.7 ± 0.3 (0.4–1.5)	<0.01
3 M time to peak torque of knee extensor (ms)	581.7 ± 166.2 (210–950)	547.6 ± 157.0 (190–840)	n.s.

(Continues)

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TABLE 2 (Continued)

	Achieved group ($n = 114$)	Nonachieved group ($n = 34$)	p Value
3 M peak torque angle of knee extensor (°)	66.4 ± 9.3 (48–86)	69.9 ± 12.9 (51–96)	n.s.
3 M acceleration time of knee extensor (ms)	43.7 ± 29.9 (10–220)	44.4 ± 19.0 (10–90)	n.s.
3 M time to peak torque of knee flexor (ms)	412.1 ± 222.6 (100–1460)	429.1 ± 219.0 (70–1270)	n.s.
3 M peak torque angle of knee flexor (°)	36.0 ± 13.4 (12–86)	40.9 ± 13.4 (20–87)	0.03
3 M acceleration time of knee flexor (ms)	61.9 ± 26.4 (20–150)	72.1 ± 49.8 (30–340)	n.s.
3 M HQ ratio	0.52 ± 0.14 (0.29–0.99)	0.49 ± 0.13 (0.26–0.77)	n.s.

Note: Values are reported as mean ± standard deviation, and preoperative Tegner activity score is median (minimum–maximum). Statistically significant at $\alpha = 0.05$. Statistically significant differences were found in the preoperative waiting period, LSI and BW ratio for knee extensor and flexor strength at 3 months postoperatively and peak torque angle of the knee flexor at 3 months postoperatively. These items were used as independent factors in a multiple logistic regression analysis to investigate their association with knee flexor strength at 6 months postoperatively.

Abbreviations: 3 M, 3 months; BW, body weight; BMI, body mass index; HQ, hamstrings to quadriceps; LSI, limb symmetry index; ST, semitendinosus tendon; STG, semitendinosus and gracilis tendons.

TABLE 3 Factors associated with improvement of knee extensor strength at 6 months postoperatively.

Factors	Regression coefficient (β)	SE	OR (95% CI)	p Value
Preoperative waiting period	0.01	0.01	1.01 (1.001–1.02)	0.04
3 M LSI extensor	−0.03	0.02	0.98 (0.93–1.02)	n.s.
3 M LSI flexor	−0.08	0.03	0.92 (0.87–0.96)	<0.01
3 M BW extensor	1.07	0.99	2.91 (0.42–21.46)	n.s.
3 M BW flexor	−0.48	1.72	0.62 (0.02–17.7)	n.s.
3 M peak torque angle of knee flexor	0.01	0.01	1.01 (0.99–1.04)	n.s.

Note: Statistically significant at $\alpha = 0.05$. Dependent variable: knee flexor strength at 6 months postoperatively; independent variables: preoperative waiting period, LSI, BW ratio for knee extensor and flexor strength at 3 months postoperatively and peak torque angle of the knee flexor at 3 months postoperatively.

Abbreviations: 3 M, 3 months; ACL, anterior cruciate ligament; BW, body weight; CI, confidence interval; LSI, Limb symmetry index; OR, odds ratio; SE, standard error.

of 76.9% for knee flexor strength. The area under the curve (AUC), sensitivity and specificity were 0.82, 0.76 and 0.78, respectively (Figure 3).

DISCUSSION

The most important finding of this study was the relationship between knee flexor strength at 6 months and 3 months postoperatively after ACL reconstruction, with a clear cut-off value of 76.9% for LSI for knee flexor strength at 3 months postoperatively.

Despite the fact that more than half of ACL reconstruction procedures use HT of the knee flexor [2], most concerns are knee extensor strength [14, 31, 32, 38] and factors affecting knee flexor strength have not been adequately investigated. Recent reports have shown that ACL reconstruction with HT has an LSI of less than 90% in knee flexor strength, even two years postoperatively [6]. In the present study, the achieved group showed a very strong mean LSI of over 90% for knee flexor strength at 3 months postoperatively. One factor behind this is that our rehabilitation protocol introduced several muscle-strengthening exercises targeting the hamstrings (Table 1), with careful instruction on posture during movement to promote hamstring contraction [4] (Figure 2). It may also be influenced by the fact that postoperative rehabilitation tends to focus on the involved limb due to the time available in practice. On the other hand, aggressive rehabilitation

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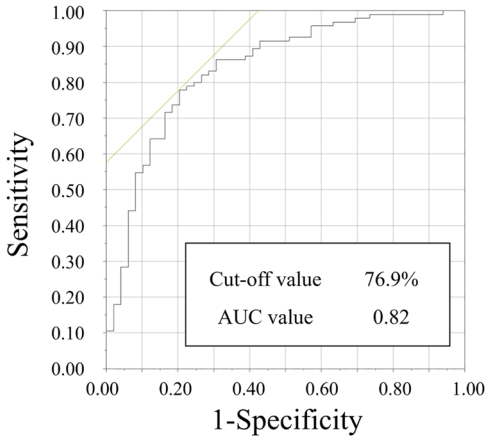

FIGURE 3 Calculation of cut-off values from knee flexor strength 3 months after ACL reconstruction. The receiver operating characteristic curve was used to calculate the cut-off value of LSI at 3 months postoperatively required to achieve the criterion value (LSI ≧ 90%) of LSI for knee flexor strength at 6 months postoperatively. The cut-off value, sensitivity, specificity and AUC value were determined to be 76.9%, 0.76, 0.78 and 0.82, respectively. ACL, anterior cruciate ligament; AUC, area under the curve; HT, hamstring tendon; LSI, limb symmetry index.

after ACL reconstruction may lead to complications such as bone tunnel enlargement [18, 35]. Our protocol avoids exercises that involve large movements of the joint early on as much as possible and incorporates a lot of closed kinetic chain exercises in terms of graft fixation and bone tunnel enlargement. Attention was also paid to postural control [4] during the exercise to reduce the anterior-posterior movement of the tibia and traction stress on the ACL, encouraging cocontraction of the quadriceps and hamstrings. Further research is needed on this protocol to determine its safety.

The hamstrings also pull the tibia backward at 20°–30° of knee joint flexion or greater and improve the stability of the knee joint in the sagittal plane during movements such as side-step cutting and single leg-landing [21, 22]. This study demonstrated that the cut-off value of knee flexor strength at 3 months postoperatively, required to achieve the criterion value at 6 months postoperatively, was 76.9%, with high statistical power (AUC 0.82, sensitivity 0.76 and specificity 0.81). Three months postoperatively is the turning point to start running [3, 8], and many reports recommend an LSI of at least 70% for knee extensor and flexor strength at that time [26, 27, 39]. Based on the results of this study, a higher target value (LSI≧76.9%) for knee flexor strength at 3 months postoperatively should be set to achieve the criterion value for knee flexor strength at 6 months postoperatively. In addition, the nonachieve group had a significantly longer preoperative waiting period. The reasons for this could not be clarified through this study. However, since a prolonged preoperative waiting period may contribute to the loss of knee extensor and flexor strength, it is important to prevent preoperative muscle weakness as much as possible [41]. In recent years, the effectiveness of prerehabilitation before ACL reconstruction has become clear [5, 10, 25], and this approach may be necessary to facilitate a return to sports after ACL reconstruction.

In addition, the peak torque angle at 3 months postoperatively was larger in the nonachieving group, suggesting that it may take more time to reach the maximum output. The reason for this is not clear, but one possibility is that it may be related to regeneration after ST harvesting during ACL reconstruction. Previous studies have reported that the regenerated musculotendinous junction is proximal [16, 17] and that knee flexor strength loss depends on the angle of flexion [24]. Adachi et al. [1] showed that the peak torque angle was shallower when additional grafting of the gracilis tendon was performed in the ST. In this study, there was no significant difference in the graft tendon used between the two groups, but this may have been influenced by the slightly higher proportion of gracilis tendons harvested in the achievement group. As ST regeneration plays an important role in improving knee flexion strength after ACL reconstruction, the relationship with the cut-off values shown in this study may also need to be investigated. However, there was no significant difference in the time to peak torque. The difference in the time to peak torque is approximately 20 ms, which is not a small difference considering that the ACL rupture reported by Koga et al. [15] occurs within 40 ms of the initial contact. The gradual rehabilitation process for returning to sports should include training for fast muscle contraction rates, such as jumping and cutting, to improve the contraction rate of knee flexor strength by the time the athlete returns to sports.

This study had some limitations. First, patients with knee flexor strength of LSI greater than 85% and less than 90% at 6 months postoperatively were excluded from the study. Since the LSI criterion for return to sports is often set at 85%–90%, those classified in this interval were excluded because they could have been classified either way, depending on the criteria employed. Second, because of the timing of hospitalisation, preoperative muscle strength could not be measured. Third, meniscal and cartilage injuries were evaluated only for the presence of the injury and not for the grade or site of the injury. Finally, there are no prospective data on the incidence of repeat ACL or hamstring injuries in this cohort. Despite these limitations, the information and criteria are clinically understandable and useful. This study identified the target knee flexor strength that should be acquired at 3 months postoperatively to achieve knee flexor

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strength at 6 months postoperatively, which is the turning point for return to sports after ACL reconstruction. In the future, it may be necessary to reconsider muscle-strengthening exercises for knee flexor strength up to 3 months postoperatively based on these results.

CONCLUSION

The cut-off value of LSI for knee flexor strength at 3 months postoperatively to achieve the criterion value of knee flexor strength at 6 months after ACL reconstruction was 76.9%. This is a criterion to aim for, considering the stress on the graft and the regeneration process of the semitendinosus tendon.

AUTHOR CONTRIBUTIONS

Takuya Sengoku, Junsuke Nakase and Satoru Demura conceived the study. Junsuke Nakase, Yoshihiro Ishida, Yusuke Yanatori and Naoki Takemoto managed and supervised the project; Takuya Sengoku, Yushin Mizuno, Yoshihiro Ishida, Yusuke Yanatori and Naoki Takemoto were responsible for investigation and analysis. Takuya Sengoku wrote the manuscript. All authors reviewed and edited the manuscript.

ACKNOWLEDGEMENTS

The authors have no funding to report.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

ETHICS STATEMENT

This study was conducted with the approval of the Ethics Review Committee of Kanazawa University (1860). Informed consent was obtained from all individuals who participated in this study.

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How to cite this article: Sengoku, T., Nakase, J., Mizuno, Y., Ishida, Y., Yanatori, Y., Takemoto, N. et al. (2024) Knee flexor strength at 6 months after anterior cruciate ligament reconstruction using hamstring tendon can be predicted from that at 3 months. *Knee Surgery, Sports Traumatology, Arthroscopy*, 1–10. https://doi.org/10.1002/ksa.12370

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