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Quadriceps strength to body weight ratio is a significant indicator for initiating jogging after anterior cruciate ligament reconstruction

T. Iwame [a,*], T. Matsuura [a], T. Okahisa [b], S. Katsuura-Kamano [c], K. Wada [a], J. Iwase [a], K. Sairyo [a]

[a] Department of Orthopedics, Tokushima University Graduate School of Biomedical Sciences, Tokushima, Japan
[b] Department of Rehabilitation, Tokushima University Hospital, Tokushima, Japan
[c] Department of Preventive Medicine, Tokushima University Graduate School of Biomedical Sciences, Tokushima, Japan

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ABSTRACT

Background: Quadriceps strength recovery after anterior cruciate ligament (ACL) reconstruction is an important criterion for progress in rehabilitation and return to sports. The purpose of this study was to determine whether quadriceps strength to body weight ratio (QS/BW) is a significant indicator for initiating jogging after ACL reconstruction.
Methods: Isokinetic quadriceps strength at 60°/s was measured and a jogging trial was completed 3 months after ACL reconstruction with hamstring tendon autograft in 83 patients (36 male, 47 female; mean age, 26.6 ± 12.4 years). Based on the jogging trial results, patients were assigned to either a successful jogging group (mean velocity ≥ 9 km/h) or an unsuccessful jogging group (mean velocity < 9 km/h). The association between QS/BW and successful jogging after surgery was investigated by multivariate logistic regression analysis and the cut-off value was determined by receiver operating characteristic analysis.
Results: Forty-four patients (53.0%) were assigned to the successful jogging group and 39 (47.0%) to the unsuccessful jogging group. QS/BW was independently associated with initiating jogging 3 months after surgery. The cut-off value of QS/BW for successful jogging was 1.45 Nm/kg (area under the curve = 0.94; sensitivity = 88.6%, specificity = 87.2%). All of the patients who initiated jogging with QS/BW of > 1.45 Nm/kg at 3 months returned to sports without recurrence or contralateral injury by 10 months after surgery.
Conclusions: QS/BW is a significant indicator for safely initiating jogging 3 months after ACL reconstruction. The cut-off value of QS/BW for initiating jogging was 1.45 Nm/kg.

1. Introduction

Anterior cruciate ligament (ACL) reconstruction is the most common surgical treatment for ACL injury [1–3]. A number of studies have reported good clinical outcomes after ACL reconstruction in terms of knee stability [1,4] and subjective assessments [5,6]. It has also been reported that rehabilitation is among the major factors contributing to favorable knee function and patient satisfaction [7,8] and reducing the presence of risk factors for recurrence of ACL injury after surgery [9–13].

* Corresponding author at: Department of Orthopedics, Tokushima University Graduate School, Institute of Biomedical Sciences, 3-18-15 Kuramoto, Tokushima-shi, Tokushima 770-8503, Japan.
E-mail addresses: tiwame@gmail.com, iwame.toshiyuki@tokushima-u.ac.jp (T. Iwame).

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Recovery of knee extensor strength is an essential requirement to proceed with rehabilitation [8,14–17]. In addition, quadriceps strength has been used as one of the criteria for determining the timing of initiating jogging and returning to sports training or competition [18–22].

In a survey of 60 orthopedic surgeons, Greenberg et al. found that initiating jogging was commonly permitted between 3 and 4 months after surgery [23]. However, they also reported that there was a wide variation in responses and no clear consensus on a specific limb symmetry index (LSI) value for quadriceps muscle strength required for initiating jogging [23]. It would therefore be helpful to identify a specific criterion that can guide progression through the postoperative protocol.

Most previous studies examining quadriceps muscle strength after ACL reconstruction have used the LSI value as an evaluation item [15–17,24–32]. However, because this value can be influenced by the uninvolved leg, muscle strength recovery of the involved leg may not be determined accurately, especially in the early postoperative phase [33–35]. For example, if improvement of muscle strength after surgery is higher in the uninvolved than in the involved side, the LSI value decreases even though muscle strength in the involved side has in fact increased. Accordingly, if muscle strength is evaluated according to LSI alone, the muscle strength of the involved leg after surgery might not be evaluated appropriately. The quadriceps strength to body weight ratio (QS/BW) could be an alternative objective index for evaluation that does not rely on the uninvolved side. In this study, we used multivariate logistic regression analysis to investigate whether QS/BW could be useful for assessing the quadriceps strength of the involved leg.

The purpose of this study was to determine whether QS/BW is a significant indicator for initiating jogging 3 months after ACL reconstruction and to determine the optimal cut-off value of QS/BW for predicting successful return to jogging. The results of this study were expected to provide clinically useful information and an indicator for return to jogging after surgery.

2. Materials and Methods

2.1. Patients

This study involved 83 patients (36 male, 47 female; mean age 26.6 ± 12.4 (range, 13–61) years) who underwent ACL reconstruction with a hamstring tendon autograft between August 2014 and March 2019. All patients underwent measurement of isokinetic quadriceps strength at 60°/s and completed a jogging trial 3 months after surgery. The following exclusion criteria were applied: bilateral knee injury, history of ACL reconstruction on the ipsilateral side, multiple knee ligament injuries requiring concomitant surgery, and a range of motion deficit in extension > 10° relative to the contralateral side. This study was approved by our institutional review board. All patients or their guardian provided written informed consent to participate in this study.

2.2. Surgical technique

Single-bundle (SB) ACL reconstruction was performed in 23 patients and double-bundle (DB) ACL reconstruction was performed in 60 patients. In the DB ACL reconstruction procedure, either the semitendinosus tendon alone or both the semitendinosus and gracilis tendons were harvested for the anteromedial bundle (AMB) and posterolateral bundle (PLB) grafts. The tibial tunnels were created at the center point of the insertion of the AMB and PLB. The femoral tunnels were created through the tibial tunnels, as described previously [36]. After the grafts were passed through the tunnels, femoral fixation was performed with titanium buttons and tibial fixation using bioresorbable screws. During SB ACL reconstruction, single femoral and single tibial tunnels were created at a position central between the original insertion of the AMB and PLB.

2.3. Rehabilitation protocol

All patients underwent the same postoperative rehabilitation protocol. Range of motion exercise and isometric strength exercise were started on postoperative day 2, and partial weight bearing with crutches and a knee brace was started from 1 week postoperatively. Full weight bearing was allowed 3 weeks after the surgery. If meniscal injury repair was performed concomitantly, partial weight bearing was started from 3 weeks and full weight bearing was allowed at 6 weeks. The rehabilitation program was designed to improve range of motion and muscle strength in the lower limbs as well as proprioceptive sensation. In the first 3 months after surgery, mainly closed kinetic chain exercises and proprioceptive training were performed. Jogging was permitted at 3 months or later and speed was increased depending on the extent of muscle strength recovery. Jumping, cutting, and agility exercises were allowed starting at 4–5 months postoperatively. Sports-specific training was started from 6 months after surgery depending on muscle strength. The rehabilitation protocol targeted return to sports by approximately 10 months after surgery.

2.4. Measurements

The demographic and clinical data collected for analysis included age, sex, height, weight, pre-injury Tegner activity scale (TAS) score, time from injury to surgery, surgical technique (SB or DB), and meniscal injury (requiring surgical repair).

The maximum isokinetic strength of the quadriceps was assessed using a Biodex System 4 Isokinetic Dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA). Patients warmed up using this system before the muscle strength test, which was performed in a seated position with 90° of hip flexion and 90° of knee flexion, and the trunk fixed to the seat. The test was performed for the contralateral leg first and then repeated for the operated leg. Five maximal effort knee flexion–extension contractions were performed at 60°/s with continuous verbal encouragement from a physiotherapist (T.O.) and the peak extension torque was recorded. All data were normalized by body weight, and the LSI score of quadriceps strength was calculated and expressed by normalizing the peak torque of the operated leg by that of the contralateral leg. Anterior knee laxity was measured using a KT-2000 arthrometer (MEDmetric Corp., San Diego, CA). Anterior tibial translation was measured as the side-to-side difference at 3 and 10 months after ACL reconstruction.

2.5. Jogging trial

A track lap of 40 m was used for the jogging trial. Patients wore a functional brace while warming up and training to jog before the trial. The trial was performed under the supervision of a physiotherapist (T.O.). The patients jogged around the track in the direction with the operated limb on the outside so that turning was performed on only the uninvolved limb. Each patient was instructed to gain speed as quickly as possible without any pain or feelings of anxiety. The patient jogged for 5 min and their velocity was calculated after the trial. Based on the jogging trial results, patients were assigned to either a successful jogging group (mean velocity $\geq$ 9 km/h) or an unsuccessful jogging group (mean velocity < 9 km/h). Jogging was defined as proceeding at a comfortable pace, regardless of the patient's current activity level [37]. We set 9 km/h as the cut-off for a successful jogging trial based on previous reports [37,38]. If the patient experienced pain or anxiety or started to limp during a trial, the trial was suspended and the patient was assigned to the unsuccessful jogging group.

2.6. Statistical analysis

Continuous variables are expressed as the mean ± standard deviation. Categorical variables are expressed as the number (percentage). The Mann–Whitney *U*-test or chi-squared test was used to compare the demographic and clinical data between the successful jogging and unsuccessful jogging groups. The results of univariate and multivariate logistic regression analyses are presented as odds ratios (OR) and 95% confidence intervals (CIs). In this study, an OR > 1 indicates that the presence of a certain exposure factor is associated with successful jogging. Statistical tests were based on two-sided probabilities. Statistical analysis was performed using the Statistical Package for Social Science version 20.0 (IBM, Armonk, NY, USA) and SAS software version 9.4 (SAS Institute Inc., Cary, NC, USA). A *P*-value < 0.05 was considered statistically significant.

2.7. Assessment strategy

Univariate and multivariate logistic regression analyses were performed to investigate the following factors: age, sex, body mass index, pre-injury TAS score, time from injury to surgery, surgical technique (SB or DB), meniscus repair, QS/BW, and LSI score. From the results of the multivariate logistic regression analysis, the cut-off value for initiating jogging after ACL reconstruction was determined using receiver operating characteristic (ROC) curves as previously described [39,40].

Table 1
Comparison of demographic and clinical data of patients in the successful and unsuccessful jogging groups.

	All (n = 83)	Successful jogging (n = 44)	Unsuccessful jogging (n = 39)	*P*
Age (years)	26.6 ± 12.4	22.5 ± 9.8	31.1 ± 13.6	0.008
Sex (male)	36 (43.4)	24 (54.5)	12 (30.8)	0.029
BW (kg)	64.5 ± 12.5	63.7 ± 12.3	65.3 ± 12.8	0.422
BMI (kg/m^2)	23.8 ± 4.0	23.5 ± 3.7	24.2 ± 4.3	0.463
TAS	7.0 ± 1.7	7.6 ± 1.3	6.4 ± 1.9	0.001
Time from injury to surgery (months)	15.7 ± 36.7	7.2 ± 13.1	25.4 ± 50.4	0.109
Surgical technique (DB)	60 (72.3)	32 (72.7)	28 (71.8)	0.925
Meniscal repair (yes)	22	11	11	0.741
3 months postoperatively				
QS/BW (Nm/kg)	141.9 ± 50.6	176.5 ± 36.2	102.9 ± 33.1	<0.0001
LSI (%)	54.8 ± 14.0	61.6 ± 8.8	47.1 ± 14.8	<0.0001
KT 2000 measurement (mm)	0.4 ± 1.1	0.6 ± 1.2	0.1 ± 1.1	0.459

Data are shown as means ± standard deviation or as number (percentage) as appropriate. BMI, body mass index; BW, body weight; DB, double-bundle; LSI, limb symmetry index; QS/BW, quadriceps strength to body weight ratio; TAS, Tegner activity scale.

3. Results

Table 1 shows the demographic and clinical data of the patients in this study. Forty-four patients (53.0%) were assigned to the successful jogging group and 39 (47.0%) to the unsuccessful jogging group. Tables 2 and 3 summarize the results of univariate and multivariate logistic regression analyses for the two groups.

Univariate analysis identified age, sex, pre-injury TAS, QS/BW, and LSI score at 3 months after surgery as significant predictors (Table 2). Multivariate logistic regression analysis showed that QS/BW at 3 months after surgery was a significant independent indicator among all variables for initiating jogging (OR, 1.16; 95% CI, 1.07–1.25; $P < 0.001$) (Table 3). ROC analysis revealed that the cut-off value of QS/BW for successful jogging 3 months after ACL reconstruction was 1.45 Nm/kg (area under the curve = 0.94; sensitivity = 88.6%, specificity = 87.2%; Figure 1).

Of the 44 patients with QS/BW of $\geq$ 1.45 Nm/kg at 3 months after surgery, 39 successfully initiated jogging. The trial was suspended for the remaining five patients because of pain, anxiety, or limping during the jogging trial. All 39 patients who successfully initiated jogging had regained muscle strength, knee laxity, and knee function, completed a single-hop test, and achieved return to sports at 10 months after ACL surgery [41]. There were no complications, such as recurrence or contralateral injury, during the study period. Of these 39 patients, the mean LSI score of quadriceps strength was 86.0 ± 10.7%, and the side-to-side difference in anterior tibial translation was 0.7 ± 0.6 mm at 10 months after ACL surgery.

4. Discussion

The most important finding of this study is that QS/BW is a significant indicator for initiating jogging at 3 months after ACL reconstruction. Quadriceps strength weakness is common after ACL injury [42,43] and ACL reconstruction [44–46], and has been associated with certain movement characteristics during walking and jogging [47,48]. In addition, eccentric quadriceps contraction is necessary to control knee flexion and provide shock absorption. A previous study suggested that a deficit in quadriceps strength contributed significantly to altered gait pattern after ACL reconstruction [49]. Therefore, insufficient quadriceps strength after ACL reconstruction could reduce the ability of the knee to attenuate shock and cause instability due to gait deviation, and has recently been suggested to contribute to knee osteoarthritis [50]. Therefore, recovering quadriceps strength after surgery is essential for rehabilitation to proceed safely and smoothly [8,14–17] and to allow for a return of normal joint kinematics and kinetics.

The LSI value is commonly used to evaluate muscle strength and balance between the involved and uninvolved legs after surgery, but it can be influenced by the uninvolved leg [34,35]. When the muscle strength of the uninvolved leg has a strong influence, the actual recovery of the involved leg might not be evaluated appropriately. In a study by Kuenze et al. [51], it was suggested that assessing lower extremity function using LSI score might be a flawed approach due to the potential effects of ACL reconstruction on the contralateral limb function; furthermore, this limitation in LSI might disproportionately affect younger individuals. It is therefore important to adequately assess the recovery of quadriceps strength in the involved leg before proceeding with subsequent steps in the rehabilitation protocol. Here we investigated whether QS/BW had validity as a significant indication for initiating jogging 3 months after ACL reconstruction. QS/BW can be evaluated over time as an objective index that is not influenced by the uninvolved side. Kuenze et al. reported that normalized knee extension torque and quadriceps activation were both strong indicators of good patient-reported outcomes after ACL reconstruction, and they established threshold values accordingly [52]. The results of our multivariate logistic regression analysis support our hypothesis that QS/BW can be a significant indicator for initiating jogging after surgery based on factors such as demographics, surgical technique, and muscle strength.

QS/BW was selected as an indirect assessment metric of the quality of the quadriceps muscle in this study. Measures of quadriceps muscle size, including the cross-sectional area (CSA) or muscle volume, could be an alternative means of evaluating quadriceps strength. A previous study reported that quadriceps CSA was related to knee extension torque, and improvement in both quadriceps CSA and muscle strength might aid in the restoration of more general knee function after

Table 2
Univariate analysis of factors associated with jogging post-anterior cruciate ligament reconstruction with a hamstring autograft.

Variable	OR	95% CI	*P*
Age (years)	0.94	0.90–0.98	<0.01
Sex (male)	2.70	1.10–6.66	0.03
BMI (kg/m^2)	0.95	0.85–1.06	0.39
TAS	1.63	1.20–2.22	<0.01
Time from injury to surgery (months)	0.98	0.95–1.00	0.07
Surgical technique (DB)	1.05	0.40–2.74	0.92
Meniscal repair	0.85	0.32–2.26	0.74
QS/BW (Nm/kg)	1.07	1.04–1.11	<0.0001
LSI (%)	1.11	1.06–1.17	<0.0001

ACL, anterior cruciate ligament; BMI, body mass index; CI, confidence interval; DB, double-bundle; LSI, limb symmetry index; OR, odds ratio; QS/BW, quadriceps strength to body weight ratio; TAS, Tegner activity scale.

Table 3
Multivariate-adjusted associations of factors associated with jogging post-anterior cruciate ligament reconstruction with a hamstring autograft.

Variable	OR	95% CI	*P*
Age (year)	0.94	0.84–1.06	0.32
Sex (male)	0.03	0.001–1.04	0.05
BMI (kg/m^2)	1.24	0.94–1.62	0.13
TAS	0.96	0.34–2.72	0.93
Time from injury to surgery (month)	1	0.96–1.04	0.91
Surgical technique (DB)	1.71	0.12–25.36	0.7
Meniscal repair	1.19	0.12–11.37	0.88
QS/BW (Nm/kg)	1.16	1.07–1.25	<0.001
LSI (%)	0.87	0.75–1.00	0.05

All independent variables included in the multivariate-adjusted models are listed in the table. ACL, anterior cruciate ligament; BMI, body mass index; CI, confidence interval; LSI, limb symmetry index; OR, odds ratio; QS/BW, quadriceps strength to body weight ratio; TAS, Tegner activity scale.

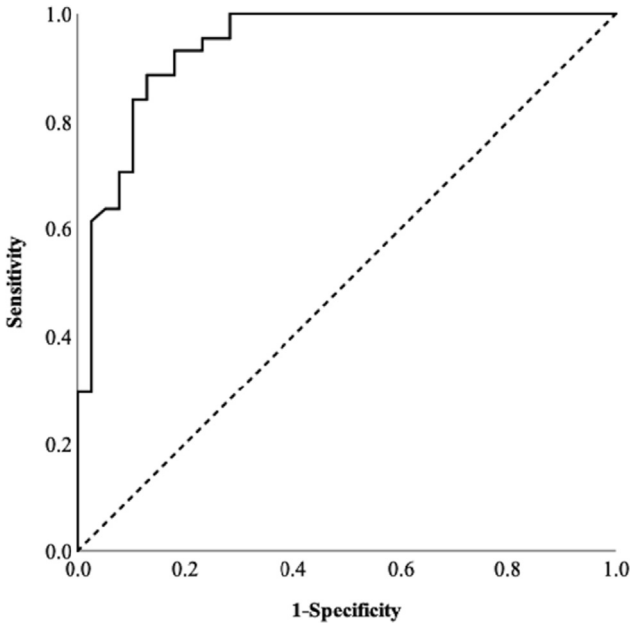

Figure 1. Receiver operating characteristics curve for determining the optimal cut-off value of quadriceps strength to body weight ratio (QS/BW). The optimal cut-off value for initiating jogging 3 months after anterior cruciate ligament reconstruction using a hamstring tendon autograft is 1.45 Nm/kg. Sensitivity and specificity of QS/BW of 1.45 Nm/kg are 88.6% and 87.2%, respectively. Area under the curve is 0.94. QS/BW, quadriceps strength to body weight ratio.

ACL reconstruction [53]. Most investigations calculated muscle CSA and volume by using computerized tomography and magnetic resonance imaging [53–55], whereas ultrasonography (US) measurement has recently been used as an additional imaging modality for evaluating muscle size [56–58]. Unlike other imaging modalities, US involves no radiation exposure. Moreover, it is inexpensive, easy to use, and portable, and has demonstrated value in the assessment of muscle CSA. US measurement of quadriceps CSA could be an alternative means of assessing knee function and may be more effective in determining readiness to initiate jogging.

Jogging was allowed relatively early in the ACL reconstruction rehabilitation protocol. Most studies have allowed jogging at 3–4 months postoperatively [23,24,26,59], although specific objective criteria for assessing this timing have not been well documented. Muneta et al. [18] reported the initiation of jogging 3 months after surgery when muscle strength had recovered to > 65% that of the uninjured leg. They arrived at this value based on changes in postoperative muscle strength over time; however, they did not describe a rationale that could suggest a protocol to guide the timing of initiating jogging. Greenberg et al. [23] found no clear consensus on a specific LSI value for initiating jogging. Establishing a specific target based on valid evidence could improve the motivation of the patients after surgery. In the present study, the cut-off value of QS/BW was determined by ROC analysis. The cut-off value derived in our study had statistically high reliability. Additionally, those patients with QS/BW of $\geq$ 1.45 Nm/kg had good clinical outcomes at 10 months after surgery. Based on our results, it may be advisable to improve QS/BW to > 1.45 Nm/kg in order to safely initiate jogging 3 months after surgery.

The results of this study suggest that QS/BW could be a reliable indicator to proceed with rehabilitation smoothly after ACL reconstruction, and may provide a specific indication of resuming jogging activity for patients after surgery. However, there are several limitations to this study. First, the number of patients was small. Further investigation with a larger number of patients is needed to confirm our findings. Second, the participants in this study were older than most patients who sustain ACL injury and undergo ACL reconstruction. However, we believe the results of this study may provide a significant indicator for initiating jogging not merely in older patients, but also in younger patients who have relatively high levels of activity. Third, the average time from injury to surgery for the participants in this study was longer than in most patients who undergo ACL reconstruction. In addition, several patients in this study were diagnosed as having an old ACL injury. The number of old ACL injuries was small but nevertheless influenced the average time from injury to surgery. Fourth, although the same postoperative rehabilitation protocol was used in all patients, we did not assess exercise performed at home, which might have affected postoperative recovery of quadriceps strength. Finally, our results were obtained in the early postoperative phase, thus further investigation is necessary to establish similar outcomes in the middle and later stages after surgery.

5. Conclusion

QS/BW ratio could be a reliable specific criterion for determining the timing of initiating jogging after ACL reconstruction using a hamstring tendon autograft. The cut-off value of QS/BW ratio for initiating jogging 3 months after surgery was 1.45 Nm/kg.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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