Knee Extensor Rate of Torque Development After Anterior Cruciate Ligament Reconstruction With Hamstring Tendon Autografts in Young Female Athletes

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Abstract

Background: For the measurement of functional deficits after anterior cruciate ligament reconstruction (ACLR) with bone-patellar-tendon bone (BTB) grafts, the knee extensor rate of torque development (RTD) is known as a relevant outcome. However, it remains unclear if the RTD is also a relevant outcome after ACLR with semitendinosus and gracilis tendon (STG) autografts. The purpose of the present study was to compare the limb symmetry index (LSI) of the RTD of the quadriceps with that of the peak torque after ACLR using STG autografts and to investigate the relationship between the self-reported functional outcome and the LSI of the torque parameters.

Methods: Eighteen young female athletes after ACLR with STG grafts (age: 16.8 ± 1.3 years; time after surgery: 8.6 ± 0.8 months). The participants had undergone three maximal voluntary isometric quadriceps tests using an isokinetic dynamometer. Using the torque-time curves, the peak torque, RTD_{100} (0 to 100 ms) and RTD_{200} (100 to 200 ms) were determined. The International Knee Documentation Committee subjective knee evaluation form (IKDC-SKF) was used to assess self-reported knee function. Comparisons of the LSI of the peak torque and RTD were performed by analysis of variance (ANOVA) with Bonferroni's correction as a post-hoc test. The Pearson correlation coefficient was used to examine the associations of the IKDC-SKF score with the LSI of the RTD and peak torque.

Results: The LSI of the peak torque and RTD_{200} was significantly lower than that of the RTD_{100} (peak torque vs RTD_{100}: $P = 0.017$; RTD_{200} vs RTD_{100}: $P = 0.015$). The LSI of the peak torque was positively correlated with the IKDC-SKF score ($R = 0.621$; $P = 0.006$).

Conclusions: The peak torque and RTD_{200} were more sensitive for detecting inter-limb differences in quadriceps function than RTD_{100}. The IKDC-SKF score was correlated with the LSI of the quadriceps peak torque but not with that of the RTD. The peak torque of the quadriceps was considered an appropriate screening for functional recovery after ACLR with STG grafts.

Background

Anterior cruciate ligament (ACL) injury is a serious sports trauma and accounts for 20%-25% of all sports-related injuries to the knee (1, 2). Although ACL reconstruction (ACLR) can restore joint stability (3, 4), many problems have been reported after ACLR, such as secondary ACL injury, low subjective knee function and a low rate of return to pre-injury level of sports (5–9). Patients are susceptible to secondary ACL injuries, such as ipsilateral grafts and/or contralateral ACL injuries, after returning to sports (9). A meta-analysis reported that the incidence of secondary ACL injury after returning to sports was 23% (95% CI: 16%-30%) (9). Therefore, there is an urgent clinical need to prevent secondary ACL injury after ACLR.

The International Knee Documentation Committee Subjective Knee Evaluation Form (IKDC-SKF), known as a subjective method for evaluating functional knee outcomes, has revealed lower knee function in ACLR patients at even 4 years after ACLR than in uninjured subjects (7). Furthermore, 40–60% of athletes cannot return to their pre-injury level of sports after ACLR (5, 6, 8). One of the factors affecting these problems is insufficient functional recovery after ACLR, likely causing the high incidence of secondary ACL injury, low subjective knee function and low ratio of return to sports (10). Therefore, clinicians should consider the importance of fully restoring knee function after ACLR and post-operative rehabilitation.

Quadriceps femoris dysfunction after ACLR is considered a significant problem (11). The rate of torque development (RTD) of the quadriceps has been proposed as an index of functional recovery after ACLR (12–17). The RTD is calculated from the slope of the torque-time curve, which reflects the ability for instantaneous force production and development (18). The RTD within 100 msec after torque production is affected by the neural drive and firing motor unit frequency (19). However, the RTD after 100 msec is affected by the stiffness of the muscle-tendon complex and the peak torque production potential (19, 20). Recent studies have shown that the RTD of the injured limb is lower than that of the contralateral limb after ACLR and that in healthy controls (12–16). The limb symmetry index (LSI) of the quadriceps peak torque was reported to be approximately 80% at 6 months after ACLR, while that of the RTD was only 50–70% (14, 15). Therefore, the RTD can reveal quadriceps dysfunction after ACLR.

ACLR with bone-patellar-tendon bone (BTB) grafts alters the patellar tendon stiffness (21–23); thus, the RTD is affected by not only the neural drive but also musculotendinous architectural changes. Furthermore, the difference in the LSI of the RTD and peak torque would be affected by the BTB graft rather than ACLR. Semitendinosus and gracilis tendon (STG) grafts and BTB grafts have been commonly used for ACLR (21, 23). ACLR with STG grafts does not invade the patellar tendon and, as such, is less effective on the RTD than ACLR with BTB grafts. After ACLR with STG grafts, the quadriceps peak torque LSI was reported to be 80–90%, and the LSI of the RTD was reported to be 90% (12, 17, 24). However, no report has investigated the associations of RTD after ACLR with STG grafts and the relationship with the self-reported function. Therefore, this study aimed to compare the LSI of the quadriceps RTD with that of the peak torque after ACLR with STG tendon autografts and to investigate the relationship between the self-reported function and LSI of the torque parameters. We hypothesized that there was no difference in the LSI of the RTD or peak torque and that the LSI of the RTD and peak torque was significantly correlated with the IKDC-SKF score.

Methods

Participants

Eighteen young female athletes after ACLR with STG tendon autografts (25, 26) participated in the present study (age: 16.8 ± 1.3 years; height: 160.6 ± 4.6 cm; body weight: 56.3 ± 6.6 kg; time after surgery: 8.6 ± 0.8 months; pre-injury Tegner activity scales: 8.4 ± 0.9). The inclusion criteria were as follows: age younger than 18 years, unilateral ACL injury and competitive level of sports. The risk of secondary ACL injury to athletes younger than18 years is considered high (27); thus, participants younger than 18 years were included in the study. All participants with a history of any orthopaedic surgery other than ACLR, neurological disorders of the lower limb or complicated ligament injuries requiring additional procedures (posterior cruciate ligament injury and medial collateral ligament injuries) were excluded from this study. The time from injury to surgery was 3.1 ± 3.5 months. Six participants had sustained ACL injuries to their right side, and 12 participants had injured their left side. Five participants underwent concomitant meniscus repair.

All the participants completed a standardized rehabilitation protocol. Quadriceps strengthening was started with the straight leg raising from 2 days after surgery, squatting with a knee flexion range of motion larger than 60° from 1 week after surgery and quadriceps setting from 2 weeks after surgery. Leg extension exercises with larger angles of knee flexion (> 60°) were started 6 weeks after surgery. The participants started running at 12 weeks and were allowed to jump and sprint with submaximal effort from 5 months. They were allowed to return to sports approximately 9 months after surgery. The rehabilitation protocol was progressed based on the postoperative period. In this study, all the participants were tested between 8 and 10 months after the surgery. The present study was approved by the Institutional Review Board of the authors' affiliated institution (approval number: 18–64). All the participants and their guardians received a written document explaining the study objectives and procedures and were required to provide written informed consent before participating in the research activities.

Procedures

Each participant performed a 5-minute warm-up using a stationary bike with a self-selected speed (28). After the warm-up, each participant performed 3 practice sets of 5-second maximal voluntary isometric contraction (MVIC) of the knee extensors before the actual measurement. The knee extension torque was recorded using an isokinetic dynamometer (Biodex System 3 isokinetic dynamometer; Biodex Medical Systems, Inc., Shirley, NY). The sampling rate was set at 100 Hz. All trials were performed with the hip at 90° and knee at 70° of flexion (28). Straps were firmly fastened around the patient's chest, waist and distal thigh for stabilization (13). A shin pad was placed two finger widths above the lateral malleolus (13). Before the test, the participant was instructed to extend the knee "as fast as and as much as possible" and practiced for familiarization using visual feedback from the Biodex monitor screen (28). The participant then performed each task 3 times for each leg (uninvolved limb first) with a 1-minute rest interval (28). Verbal encouragement was given to the participants to maximize the torque production during the tests.

Self-reported knee function was evaluated using the IKDC-SKF, which is an index comprising a score from 0 to 100 and scores for knee symptoms, function and sports activities. The IKDC-SKF score is highly relevant and reliable (29).

Data analysis

Custom MATLAB code (The Math Works, Inc., Natick, MA, USA) was used for data processing. The force-time signal was low-pass filtered at 6 Hz using a second-order Butterworth filter (13). The peak torque, arrival time of the peak torque and RTD were calculated from the torque-time curves (Fig. 1). The onset of muscle contraction was defined as the time when the knee extension torque exceeded the baseline by 7.5

Nm (18, 19). The RTD_{100} and RTD_{200} were also calculated (19). The RTD_{100} during the early phase of muscle contraction (0 to 100 ms) represents the influence of neural drive. Thus, the RTD_{200} during the late phase (100 to 200 ms) represents the influence of musculotendinous stiffness the and peak torque (19, 20). Both the peak torque and RTD were normalized to the body weight. The LSI of the peak torque and RTD was calculated as the percentage in the involved limb compared with that in the uninvolved limb.

Statistical analysis

Statistical analyses were performed using IBM SPSS Statistics 22 software (IBM, Chicago, IL, USA). One-way analysis of variance (ANOVA) was used to examine the difference in the LSI of the peak torque, RTD_{100} and RTD_{200}. Post-hoc comparisons were conducted using Bonferroni's correction. The paired t-test was used to examine the between-limb differences in the peak torque, arrival time of the peak torque, RTD_{100} and RTD_{200}. The Pearson correlation coefficient was used to examine the relationship between the IKDC-SKF score and LSI of the peak torque, RTD_{100} and RTD_{200}. A correlation (R) of 0.90 to 1.00 was interpreted as extremely large, 0.70 to 0.89 as very large, 0.50 to 0.69 as large, 0.30 to 0.49 as moderate, 0.10 to 0.29 as small, and less than 0.09 as trivial or no relationship (30). Furthermore, the value of d_z was calculated as the effect size (31). A d_z value greater than 0.80 was interpreted as large, 0.50 to 0.79 as moderate, and 0.20 to 0.49 as small (31). The statistical significance level was set at $P < 0.05$. The sample size was calculated using G*Power 3.1 based on previously published data (32). More than 17 participants were required to detect any between-limb difference in the RTD_{100} (80% power; $\alpha = 0.05$).

Results

One-way ANOVA revealed a significant difference in the LSI of the peak torque and RTD ($P < 0.001$). The LSI of the peak torque was significantly lower than that of the $RTD_{100,}$ as shown by the moderate effect size ($P = 0.017$; $d_z = 0.748$) (Fig. 2). The LSI of the RTD_{200} was also significantly lower than that of the $RTD_{100,}$ with a moderate effect size ($P = 0.015$; $d_z = 0.756$) (Fig. 2). No other differences in the LSIs were detected by post-hoc testing.

Concerning the inter-limb differences, the peak torque was significantly lower in the involved limb than in the uninvolved limb, with a large effect size ($P < 0.001$; $d_z = 1.366$) (Fig. 3 & Table 1). The RTD_{200} was also significantly lower in the involved limb than in the uninvolved limb, with a large effect size ($P < 0.001$; $d_z = 0.986$) (Table 1). However, no differences were found in the RTD_{100} or arrival time of the peak torque between the limbs (Table 1).

Table 1
Inter-limb differences in the peak torque, RTD_{100}, RTD_{200} and arrival time of the peak torque

	Involved limb	**Uninvolved limb**	***p*-value**	d_z
Peak torque, Nm/kg	2.5 (0.4)	3.0 (0.4)	**< 0.001**	1.366
RTD_{100}, Nm/s/kg	9.6 (3.0)	10.0 (3.1)	0.168	0.339
RTD_{200}, Nm/s/kg	6.6 (2.1)	7.6 (1.8)	**< 0.001**	0.986
Arrival time of peak torque, ms	1778 (751)	1613 (724)	0.497	0.164
Mean (SD).				
Significant differences are shown in bold.				
RTD_{100}, rate of torque development from 0 to 100 ms; RTD_{200}, rate of torque development from 100 to 200 ms.				

The LSI of the peak torque was positively correlated with the IKDC-SKF score ($R = 0.621$; $P = 0.006$) (Fig. 4-a). However, the IKDC-SKF score was not correlated with the LSI of the RTD_{100} ($R = 0.257$; $P = 0.304$) or RTD_{200} ($R = 0.322$; $P = 0.193$) (Fig. 4-b, c).

Discussion

We aimed to compare the LSI of the RTD with that of the peak torque and to determine the inter-limb difference in the peak torque and RTD after ACLR with STG grafts. We investigated the associations of the IKDC-SKF score with the LSI of the RTD and peak torque. Our findings showed that the RTD_{200} and peak torque were significantly lower in the involved limb than in the uninvolved limb. The LSI of the peak torque showed a significant correlation with the IKDC-SKF score, but there was no correlation with the RTD_{100} or RTD_{200}. These results partially support our hypothesis.

The LSI of the RTD_{100} was significantly higher than that of the RTD_{200} and peak torque. No significant difference was found in the RTD_{100} between the involved and uninvolved limbs. The present results indicate that the RTD_{100} of the involved limb is comparable to that of the uninvolved limb, supporting our hypothesis. The voluntary RTD_{100} of the quadriceps is significantly correlated with the non-voluntary RTD induced by electrical stimulation (19); thus, the RTD_{100} is considered to reflect neural drive actions such as the firing frequency effects of motor units (18). The recovery of neural function after ACLR may manifest differently depending on the type of tendon graft. The central activation ratio (CAR) measures the potential muscle exertion ability using electrical stimulation during MVIC (33–35) and is used to assess the neural drive of the quadriceps femoris after ACLR. A recent systematic review revealed that the CAR in the involved limb after ACLR with BTB grafts was lower than that in the uninvolved limb (35). By contrast, the CAR in the involved limb after ACLR with STG grafts was higher than that in the uninvolved limb (35). One possible reason for the different results between the studies was that post-operative pain affected the neural drive. Anterior knee pain after ACLR has been determined in 48% of patients receiving BTB grafts and in 20% of those receiving STG grafts at 6 months after ACLR (21). Another study showed a positive result for anterior knee pain in 73% of patients with BTB grafts and 35% of patients with STG grafts at 8 months after ACLR (21, 23). Regarding the RTD_{100} after ACLR, the LSI at 6 months after ACLR with BTB grafts was reported to be 49% (14), and the LSI at 11 months after ACLR with BTB or STG grafts was 72% (16). In our study, the RTD_{100} was 95.9%, which was higher than that in previous studies, indicating that the RTD_{100} recovered after ACLR with STG grafts. Therefore, post-operative pain due to differences in the graft type may have affected neural drive recovery after ACLR.

The RTD_{200} and peak torque were significantly lower in the involved limb than in the uninvolved limb. No difference was found in the LSI of the peak torque or RTD_{200}, indicating that the RTD_{200} is an index for detecting between-limb differences as well as the peak torque. The RTD_{200} is affected by structural factors with musculotendinous stiffness (20). A previous study reported structural changes, such as an increased cross-sectional area and decreased stiffness in the patellar tendon after ACLR with BTB grafts (22). In an animal study, the duration of patellar tendon stiffness recovery was approximately 1 year (36, 37). The LSI of the RTD_{200} at 6 months after ACLR with BTB grafts was 43% (14); even at 4 years after ACLR with BTB or STG grafts, it was up to 78% (12). In our study, the LSI of the RTD_{200} was 86.0%, which is higher than that reported previously (12, 14). Therefore, the RTD_{200} of the quadriceps after ACLR with STG grafts may be less likely to decrease than that after ACLR with BTB grafts. However, the RTD_{200} is affected by structural factors and musculotendinous stiffness (20); thus, the RTD_{200} after ACLR with BTB grafts was lower than that after ACLR with STG grafts. Additional studies should be conducted to clarify the effects of the graft type on RTD_{200} recovery after ACLR.

The LSI of the peak torque was positively correlated with the IKDC-SKF score. Thus, the IKDC-SKF score was not significantly correlated with the LSI of the RTD_{100} or RTD_{200}. These results do not support our hypothesis that the LSI of the RTD and peak torque is significantly correlated with the IKDC-SKF score. These study results are similar to those of other studies showing that the IKDC-SKF score was significantly correlated with the LSI of the peak torque (38, 39). However, the LSI of the RTD_{100} and RTD_{200} was not correlated with the IKDC-SKF score. At 3 months after ACLR, the RTD of the involved limb showed a significant positive correlation with the IKDC-SKF score (13). In contrast, there was no correlation between the LSI of the RTD and IKDC-SKF score, even at 4 years after ACLR (12). The cause may be the difference in the IKDC-SKF scores; the IKDC-SKF score was 66.5 points at 3 months after ACLR (13) and 86.8 points at 4 years after ACLR (12). The IKDC-SKF score in this study was 86.3 points; thus, a high IKDC-SKF score may also influence the results of any correlation between the LSI of the RTD and the IKDC-SKF score. No significant correlation was found between the LSI of the RTD and the IKDC-SKF score in the present study, but the peak torque could reflect subjective knee function after ACLR with STG grafts. The peak torque after ACLR was reported to be related to the kinetic asymmetry between the involved and uninvolved leg during landing (40–42). However, previous studies of the RTD after ACLR have been limited to the association with the kinetics of walking and running, such that its usefulness as a functional screening tool remains unproven (7, 43). Therefore, the peak torque of the quadriceps should be considered a more useful index to assess functional recovery after ACLR.

Some limitations of this study should be addressed. First, the participants were limited to young female athletes. Age and sex differences might affect knee extension torque (44, 45); thus, the present results might apply to young female athletes only. Second, all the participants in this study had undergone ACLR with STG grafts. Different types of ACLR might lead to different results. Finally, knee function in the present study was assessed based on the subjective knee score and was not a result of functional dynamic tasks.

Conclusions

The present study shows that the LSI of the peak torque and RTD_{200} was significantly lower than that of the RTD_{100}. The IKDC-SKF score was significantly correlated with the LSI of the peak torque but not with that of either the RTD_{100} or RTD_{200}. These results suggest that the peak torque of the quadriceps is appropriate for the functional screening of female athletes after ACLR with STG grafts.

Abbreviations

ACLR: anterior cruciate ligament reconstruction

RTD: rate of torque development

LSI: limb symmetry index

STG: semitendinosus and gracilis

BTB: bone-patellar-tendon bone

IKDC-SKF: International Knee Documentation Committee subjective knee evaluation form

ANOVA: analysis of variance

MVIC: maximal voluntary isometric contraction

CAR: central activation ratio

Declarations

Ethics approval and consent to participate

All participants and their guardians signed written informed consent forms prior to participating in the present study. This study was approved by the Institutional Review Board of Hokkaido University (approval number: 18-64). All methods were carried out in accordance with the Declaration of Helsinki.

Consent for publication

Not applicable.

Availability of data and materials

The datasets and analyses in the present study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

Funding

None declared.

Authors' contributions

M.Su. was involved in the design of this study, acquisition and analysis of the data, and writing of the article. T.I. and M.Sa. were involved in the design of this study and writing of the article. H.M., Y.I., Y.A. and H.T. were involved in the design of this study. All authors were involved in the interpretation of the results and revision of the article have approved the final version of the article.

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References

1. Majewski M, Susanne H, Klaus S. Epidemiology of athletic knee injuries: A 10-year study. Knee. 2006;13(3):184-8.
2. Swenson DM, Collins CL, Best TM, Flanigan DC, Fields SK, Comstock RD. Epidemiology of knee injuries among U.S. high school athletes, 2005/2006-2010/2011. Med Sci Sports Exerc. 2013;45(3):462-9.
3. Griffin LY, Albohm MJ, Arendt EA, Bahr R, Beynnon BD, Demaio M, et al. Understanding and preventing noncontact anterior cruciate ligament injuries: a review of the Hunt Valley II meeting, January 2005. Am J Sports Med. 2006;34(9):1512-32.

4. Maletis GB, Granan LP, Inacio MC, Funahashi TT, Engebretsen L. Comparison of community-based ACL reconstruction registries in the U.S. and Norway. J Bone Joint Surg Am. 2011;93 Suppl 3:31-6.
5. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. Br J Sports Med. 2014;48(22):1613-9.
6. Novaretti JV, Franciozi CE, Forgas A, Sasaki PH, Ingham SJM, Abdalla RJ. Quadriceps strength deficit at 6 Months after ACL reconstruction does not predict return to preinjury sports level. Sports Health. 2018;10(3):266-71.
7. Pamukoff DN, Montgomery MM, Choe KH, Moffit TJ, Garcia SA, Vakula MN. Bilateral alterations in running mechanics and quadriceps function following unilateral anterior cruciate ligament reconstruction. J Orthop Sports Phys Ther. 2018;48(12):960-7.
8. Webster KE, McPherson AL, Hewett TE, Feller JA. Factors associated with a return to preinjury level of sport performance after anterior cruciate ligament reconstruction surgery. Am J Sports Med. 2019;47(11):2557-62.
9. 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):1861-76.
10. 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):946-51.
11. Petersen W, Taheri P, Forkel P, Zantop T. Return to play following ACL reconstruction: a systematic review about strength deficits. Arch Orthop Trauma Surg. 2014;134(10):1417-28.
12. Davis HC, Troy Blackburn J, Ryan ED, Luc-Harkey BA, Harkey MS, Padua DA, et al. Quadriceps rate of torque development and disability in individuals with anterior cruciate ligament reconstruction. Clin Biomech (Bristol, Avon). 2017;46:52-6.
13. Hsieh CJ, Indelicato PA, Moser MW, Vandenborne K, Chmielewski TL. Speed, not magnitude, of knee extensor torque production is associated with self-reported knee function early after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2015;23(11):3214-20.
14. Kline PW, Morgan KD, Johnson DL, Ireland ML, Noehren B. Impaired quadriceps rate of torque development and knee mechanics after anterior cruciate ligament reconstruction with patellar tendon autograft. Am J Sports Med. 2015;43(10):2553-8.
15. Knezevic OM, Mirkov DM, Kadija M, Nedeljkovic A, Jaric S. Asymmetries in explosive strength following anterior cruciate ligament reconstruction. Knee. 2014;21(6):1039-45.
16. Larsen JB, Farup J, Lind M, Dalgas U. Muscle strength and functional performance is markedly impaired at the recommended time point for sport return after anterior cruciate ligament reconstruction in recreational athletes. Hum Mov Sci. 2015;39:73-87.
17. Kuenze C, Lisee C, Birchmeier T, Triplett A, Wilcox L, Schorfhaar A, et al. Sex differences in quadriceps rate of torque development within 1year of ACL reconstruction. Phys Ther Sport. 2019;38:36-43.

18. Aagaard P, Simonsen EB, Andersen JL, Magnusson P, Dyhre-Poulsen P. Increased rate of force development and neural drive of human skeletal muscle following resistance training. J Appl Physiol (1985). 2002;93(4):1318-26.
19. Andersen LL, Aagaard P. Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. Eur J Appl Physiol. 2006;96(1):46-52.
20. Bojsen-Moller J, Magnusson SP, Rasmussen LR, Kjaer M, Aagaard P. Muscle performance during maximal isometric and dynamic contractions is influenced by the stiffness of the tendinous structures. J Appl Physiol (1985). 2005;99(3):986-94.
21. Feller JA, Webster KE. A randomized comparison of patellar tendon and hamstring tendon anterior cruciate ligament reconstruction. Am J Sports Med. 2003;31(4):564-73.
22. Reeves ND, Maganaris CN, Maffulli N, Rittweger J. Human patellar tendon stiffness is restored following graft harvest for anterior cruciate ligament surgery. J Biomech. 2009;42(7):797-803.
23. Shaieb MD, Kan DM, Chang SK, Marumoto JM, Richardson AB. A prospective randomized comparison of patellar tendon versus semitendinosus and gracilis tendon autografts for anterior cruciate ligament reconstruction. Am J Sports Med. 2002;30(2):214-20.
24. Kuenze C, Lisee C, Pfeiffer KA, Cadmus-Bertram L, Post EG, Biese K, et al. Sex differences in physical activity engagement after ACL reconstruction. Phys Ther Sport. 2019;35:12-7.
25. Yasuda K, Kondo E, Ichiyama H, Kitamura N, Tanabe Y, Tohyama H, et al. Anatomic reconstruction of the anteromedial and posterolateral bundles of the anterior cruciate ligament using hamstring tendon grafts. Arthroscopy. 2004;20(10):1015-25.
26. Yasuda K, Kondo E, Ichiyama H, Tanabe Y, Tohyama H. Clinical evaluation of anatomic double-bundle anterior cruciate ligament reconstruction procedure using hamstring tendon grafts: comparisons among 3 different procedures. Arthroscopy. 2006;22(3):240-51.
27. Grassi A, Macchiarola L, Lucidi GA, Stefanelli F, Neri M, Silvestri A, et al. More than a 2-Fold risk of contralateral anterior cruciate ligament injuries compared with ipsilateral graft failure 10 years after primary reconstruction. Am J Sports Med. 2020;48(2):310-7.
28. Pua YH, Mentiplay BF, Clark RA, Ho JY. Associations among quadriceps strength and rate of torque development 6 weeks post anterior cruciate ligament reconstruction and future hop and vertical jump performance: A prospective cohort study. J Orthop Sports Phys Ther. 2017;47(11):845-52.
29. Irrgang JJ, Anderson AF, Boland AL, Harner CD, Kurosaka M, Neyret P, et al. Development and validation of the international knee documentation committee subjective knee form. Am J Sports Med. 2001;29(5):600-13.
30. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41(1):3-13.
31. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175-91.
32. Jordan MJ, Aagaard P, Herzog W. Rapid hamstrings/quadriceps strength in ACL-reconstructed elite alpine ski racers. Med Sci Sports Exerc. 2015;47(1):109-19.

33. Hart JM, Pietrosimone B, Hertel J, Ingersoll CD. Quadriceps activation following knee injuries: a systematic review. J Athl Train. 2010;45(1):87-97.
34. Kent-Braun JA, Le Blanc R. Quantitation of central activation failure during maximal voluntary contractions in humans. Muscle & Nerve. 1996;19(7):861-9.
35. Lisee C, Lepley AS, Birchmeier T, O'Hagan K, Kuenze C. Quadriceps strength and volitional activation after anterior cruciate ligament reconstruction: A systematic review and meta-analysis. Sports Health. 2019;11(2):163-79.
36. Cabaud HE, Feagin JA, Rodkey WG. Acute anterior cruciate ligament injury and augmented repair. Experimental studies. Am J Sports Med. 1980;8(6):395-401.
37. Hanselmann KF, Dürselen L, Augat P, Claes L. Patella position and biomechanical properties of the patellar tendon 1 year after removal of its central third. Clinical Biomechanics. 1997;12(4):267-71.
38. Harput G, Ozer H, Baltaci G, Richards J. Self-reported outcomes are associated with knee strength and functional symmetry in individuals who have undergone anterior cruciate ligament reconstruction with hamstring tendon autograft. Knee. 2018;25(5):757-64.
39. 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):2242-9.
40. Ithurburn MP, Paterno MV, Ford KR, Hewett TE, Schmitt LC. Young athletes with quadriceps femoris strength asymmetry at return to sport after anterior cruciate ligament reconstruction demonstrate asymmetric single-leg drop-landing mechanics. Am J Sports Med. 2015;43(11):2727-37.
41. Palmieri-Smith RM, Lepley LK. Quadriceps strength asymmetry after anterior cruciate ligament reconstruction alters knee joint biomechanics and functional performance at time of return to activity. Am J Sports Med. 2015;43(7):1662-9.
42. Schmitt LC, Paterno MV, Ford KR, Myer GD, Hewett TE. Strength asymmetry and landing mechanics at return to sport after anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 2015;47(7):1426-34.
43. Blackburn JT, Pietrosimone B, Harkey MS, Luc BA, Pamukoff DN. Quadriceps function and gait kinetics after anterior cruciate ligament reconstruction. Med Sci Sports Exerc. 2016;48(9):1664-70.
44. Iriuchishima T, Shirakura K, Horaguchi T, Wada N, Sohmiya M, Tazawa M, et al. Age as a predictor of residual muscle weakness after anterior cruciate ligament reconstruction. Knee Surg Sports Traumatol Arthrosc. 2012;20(1):173-8.
45. Ueda Y, Matsushita T, Araki D, Kida A, Takiguchi K, Shibata Y, et al. Factors affecting quadriceps strength recovery after anterior cruciate ligament reconstruction with hamstring autografts in athletes. Knee Surg Sports Traumatol Arthrosc. 2017;25(10):3213-9.

Figures

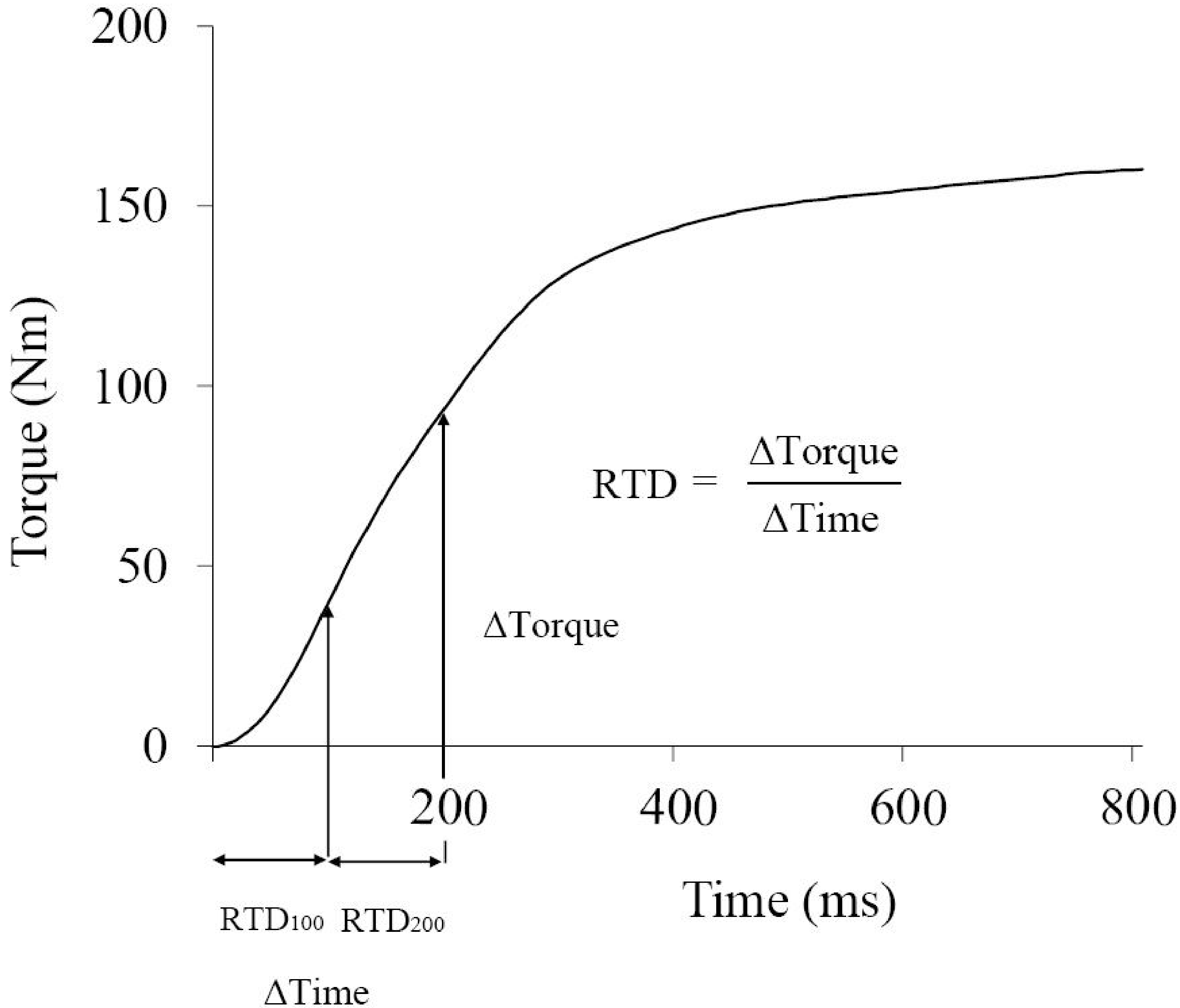

Figure 1

Rate of torque development (RTD) from the slope of the torque-time curve. RTD100 is calculated from 0 to 100 ms, and RTD200 is calculated from 100 to 200 ms.

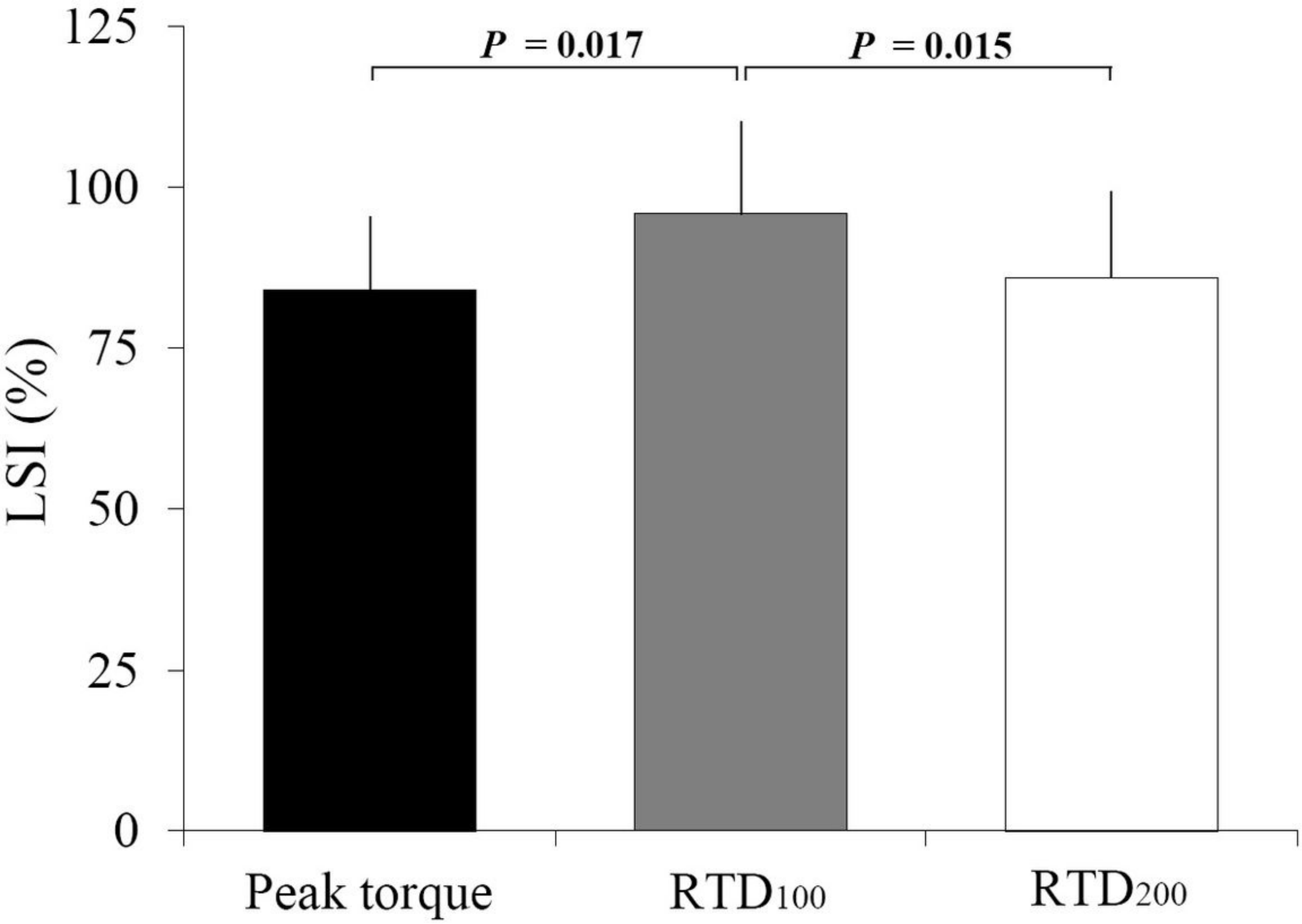

Figure 2

LSI of the peak torque and RTD. P values indicate the results of post-hoc tests. RTD, rate of torque development.

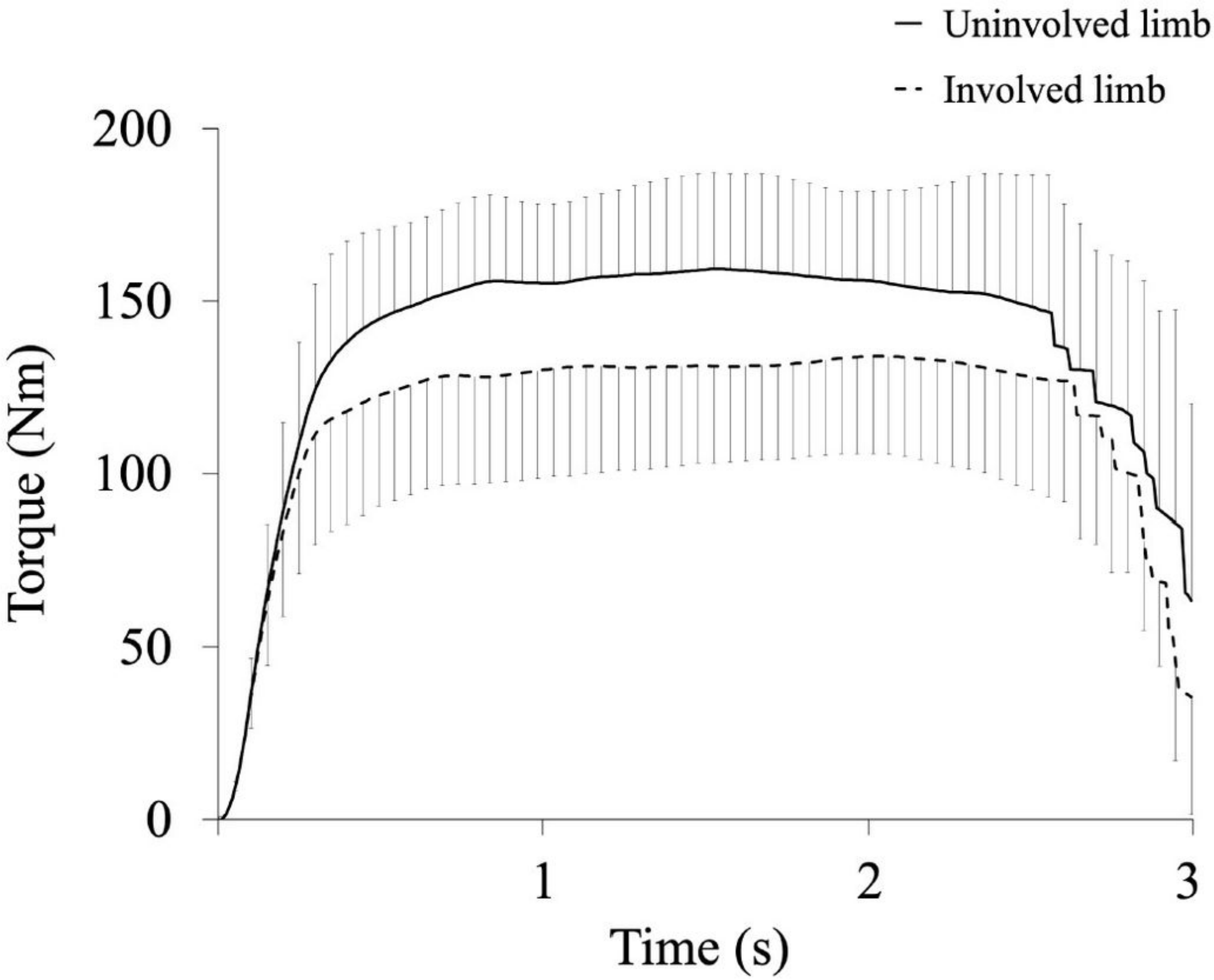

Figure 3

Average torque-time curve of all participants. Solid line, uninvolved limb. Dotted line, involved limb.

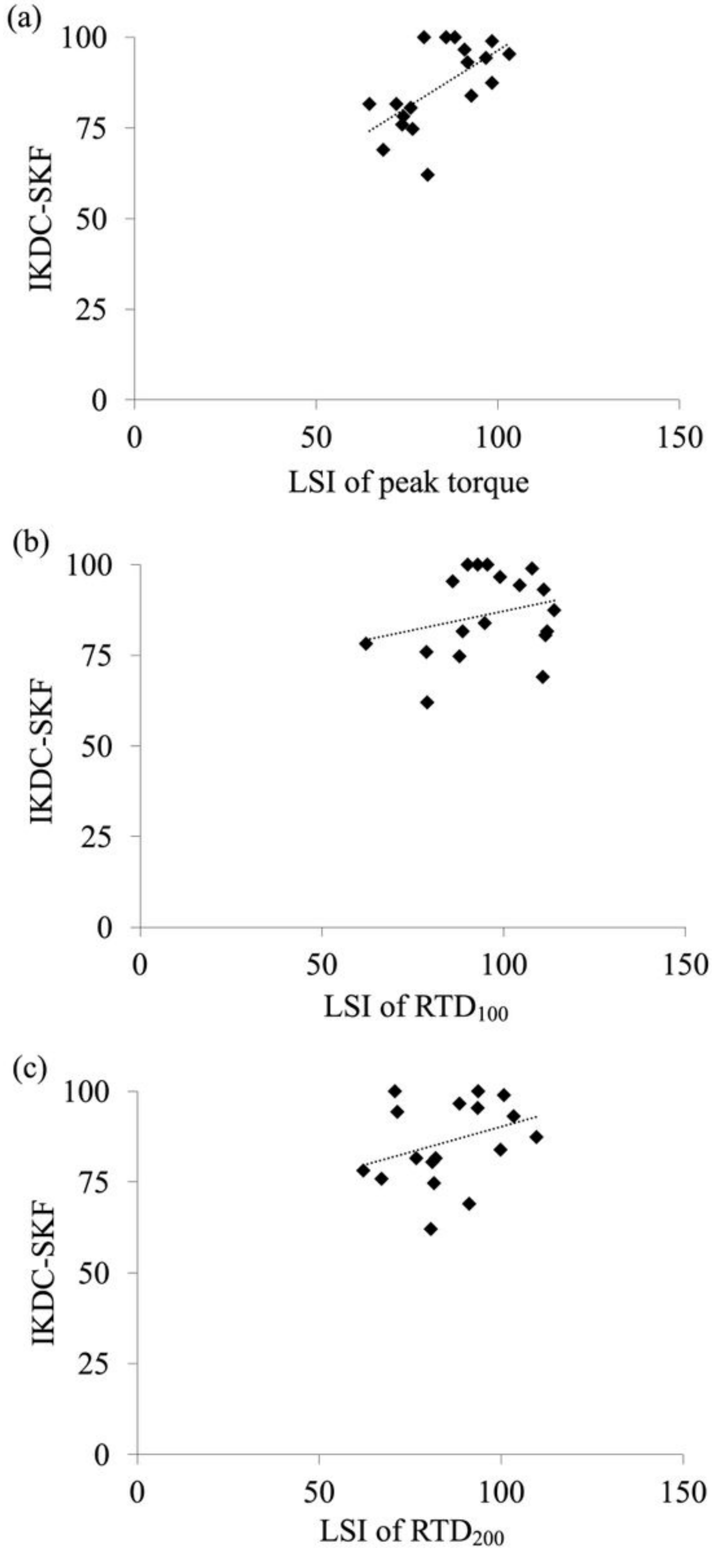

Figure 4

Relationship between the IKDC-SKF score and the LSI of the torque parameters. a. peak torque, b. RTD100, c. RTD200.