||原 著||

Relationships between jumping height and power, force and velocity during one-legged vertical jumps

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Key words：1. ACL reconstructed knee　2. vertical jump　3. accelerator

[Purpose] To determine the deficit in one-legged vertical jumping ability and to clarify the relationships between maximum jumping height and maximum power, force and velocity during one-legged vertical jumps after anterior cruciate ligament reconstruction (ACL-R) compared with healthy subjects. **[Subjects]** Twenty-five healthy subjects (10 males and 15 females) and 32 ACL-R patients (18 males and 14 females) participated in this study. **[Methods]** The isokinetic quadriceps femoris strength and one-legged vertical jumping ability evaluated by the height, power, force and velocity were measured in all subjects. **[Results]** The maximum height of the one-legged vertical jumps was only significantly correlated with the maximum force in the healthy subjects ($p < 0.05$). In contrast, for the involved and uninvolved legs in the ACL-R patients, the maximum jumping height was significantly correlated with the maximum power, force and velocity during one-legged vertical jumps ($p < 0.05$). **[Conclusions]** These findings suggest the importance of a knee strategy during one-legged vertical jumps for rehabilitation after ACL-R. Assessment of the jumping ability after ACL-R may be determined by the maximum power instead of the maximum jumping height.

Introduction

There is a high incidence of anterior cruciate ligament (ACL) injury among people participating in sports. Female adolescents suffer ACL injuries at a greater rate than male adolescents participating in the same sports. In the United States, an estimated 38,000 ACL injuries occur annually in girls and women during athletics[1]. Giving way of the knee frequently occurs after ACL injury. The recurrence of this symptom commonly leads to the early development of knee arthritis in ACL-injured patients[2]. In an attempt to prevent knee arthritis, ACL reconstruction (ACL-R) surgery is frequently adopted.

In a clinical setting, the knee function after ACL-R should not only be estimated using muscular strength tests but also by functional performance tests. Closed kinetic chain activities such as vertical jumping tests have been developed to evaluate the strength and function of the lower extremity in patients[3,4] and are used to identify differences between the injured and uninjured sides in ACL-deficient patients[5]. Commonly, side-to-side differences of less than about 10% in the strength and performance of jumping tests are used as criteria for the transition to returning to competitive play[6].

Evaluation of vertical jumping ability is usually only limited to height measurements. Previous studies have shown significant correlations between knee extensor strength and jumping height[4,7,8]. However, in some cases, the one-legged vertical jumping ability did not recover despite the recovery of the quadriceps femoris muscle strength[9]. Kinetic factors have been suggested to contribute to the jumping ability of a knee injury patient[10,11]. Thus, inclusion of measurements of parameters that describe kinetic factors may provide a better assessment of a patient's jumping ability.

Kinetic factors such as the power, force and velocity estimated by an accelerator can provide useful information for evaluating the load and stress on the body[12]. Some researchers have investigated the reliability of the ground reaction force on a force platform during a vertical jump. They concluded that the peak force measured

・片脚垂直跳び時の跳躍高と筋パワー・筋出力・速度の関係
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during one-legged vertical jumps is reliable and may provide an alternative method for evaluating lower extremity functional strength[13]. The vertical velocity was obtained by integrating with respect to time the vertical acceleration[14]. Power is simply the rate of change of work. Another way to express power is the product of force and velocity. We considered that the power, force and velocity can be used as a better index for evaluating the burden and stress on the body and the jumping ability during one-legged vertical jumps.

However, only a few studies to date have compared the differences in maximum quadriceps femoris muscle strength and the maximum height, power, force and velocity during one-legged vertical jumps between patients and healthy subjects. In addition, the relationships between the maximum height and the maximum power, force and velocity during one-legged vertical jumps remain to be fully elucidated. Therefore, the purposes of the present study were to determine (1) the deficits in maximum quadriceps femoris muscle strength and the maximum height, power, force and velocity during one-legged vertical jumps on the involved side in ACL-R patients and (2) the relationships between the maximum height and the maximum power, force and velocity during one-legged vertical jumps on the involved and uninvolved sides in ACL-R patients and the dominant side in healthy subjects.

The authors hypothesized that the outcomes would not show postoperative deficits in the maximum power, force and velocity during one-legged vertical jumps and that the maximum height was not significantly correlated with the power, force and velocity.

Subject and Methods

Subjects

Twenty-five healthy subjects (10 males and 15 females) and 32 ACL-R patients (18 males and 14 females) at 6 to 12 months after surgery participated in the study. All the ACL-R patients underwent the same surgical procedure using a hamstring autograft (semitendinosus/gracilis). All the subjects provided written informed consent to the authors before study participation. The study protocol was approved by the institutional review board of the authors' institution. The demographic data for the healthy subjects and ACL-R patients are shown in Table 1.

Table 1. Demographic data for the healthy subjects and ACL-R patients.

		Healthy Subjects (25)	ACL-Rpatients (32)
Ratio of male and female		10 : 15	18 : 14
Age	(y)	22.1 ± 2.1	21.6 ± 5.9
Body Height	(cm)	164.3 ± 8.0	167.8 ± 7.7
Body Weight	(kg)	56.9 ± 6.6	65.5 ± 13.5

All values are expressed as means(±SD)

Methods

A BIODEX System III (Biodex Medical Inc., USA) was used for measurements of the quadriceps femoris muscle strength (Fig. 1). The subjects were asked to extend their legs while seated on the BIODEX. The weight of the limb was recorded and corrected for gravity. Before data collection, the subjects performed at least four practice repetitions at the subjective maximum effort. The peak torque values at an angular velocity of 60 deg/s were measured four times. The maximum values were adjusted to the body weight and used as a dependent measure of the muscle strength. The muscle strength values were obtained for the dominant side (leg usually used for kicking a soccer ball[15]) in the healthy subjects and the involved and uninvolved sides in the ACL-R patients.

The one-legged vertical jumping ability of the patients was measured at 6 to 12 months after ACL-R. Prior to testing, the subjects received instructions for the jumping tests, were given sufficient time to familiarize themselves with the protocol and were allowed to practice under the direct supervision of the authors. The test was carried out after the last exercise

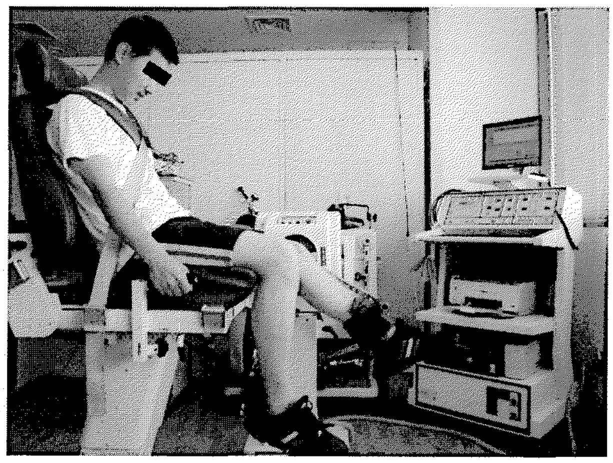

Fig. 1. Measurement of quadriceps femoris muscle strength using the BIODEX System III.

during instruction. For the ACL-R patients, the uninvolved side was tested first, followed by the involved side. For the healthy subjects, only the dominant side was tested.

A MYOTEST System (Fig. 2) and a Jump MD System (Takei Company, Japan) were used to assess the vertical jumping ability. The MYOTEST System consists of an accelerometer that was attached to a waist belt and used to measure the vertical acceleration. The MYOTEST System then converted the acceleration into power (W), force (N) and velocity (cm/s). The Jump MD System converted the length of a line into a jumping height. The power and force were normalized to the body weight for each subject.

The initial position for the one-legged vertical jumping test was a squatting position with the hands placed on the waist to decrease any counter-reaction (Fig. 3). The subjects were asked to immediately jump upward with the goal of achieving the maximum height and then to land both legs on the ground simultaneously to reduce the risk of injury. During the measurements, the subjects' hands remained on their waist. Two or three practice trials were carried out before the data were recorded. The authors compared with the heights between the practices and the tests. The data for the test in which the subjects attained the highest height were adopted.

All statistical analyses were performed using the software Statistical Package for Social Sciences Version 12 (SPSS Inc., Japan). Descriptive statistics including the mean values ± standard deviation were obtained. In the present study, a post-hoc test could not be used, because the involved and uninvolved sides of the ACL-R patients were paired, whereas the involved side and the dominant side or the uninvolved side and the dominant side were unpaired. We compared the involved and uninvolved sides of the ACL-R patients using paired t-tests. Student's t-tests were used for comparisons of the involved or uninvolved side of the ACL-R patients and the dominant side of the healthy subjects. The level of significance was determined as $p < 0.05/3 = 0.017$, considering the multiple performances. Pearson product moment correlations were used to detect the relationships among parameters. The level of significance was determined as $p < 0.05$. The reproducibility of the one-legged vertical jumping ability measurements with the MYOTEST System and the Jump MD System were tested using the intraclass correlation coefficient (ICC (1.1)).

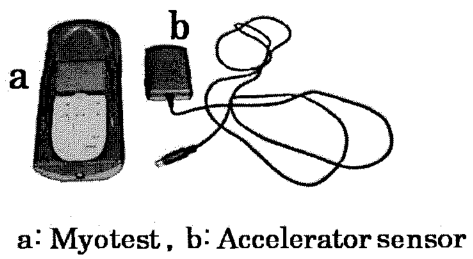

Fig. 2. The MYOTEST system (a) and its accelerator sensor (b).

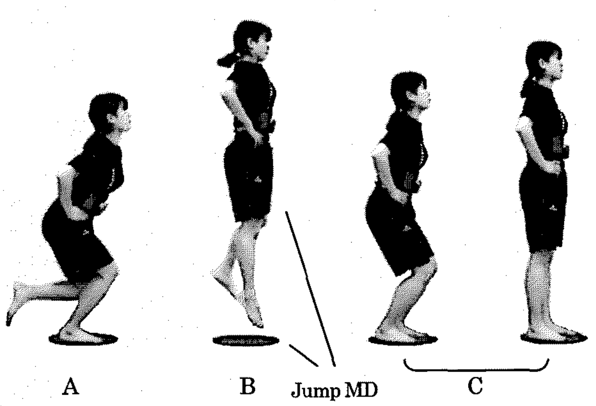

Fig. 3. Measurement of a one-legged vertical jump.
A: Start position. B: Jumping upward. C: Landing.

Results

There were no significant differences in age, height, male/female ratio or body weight between the healthy subjects and the ACL-R patients. The reproducibilities of the one-legged vertical jumping ability assessments using the MYOTEST System and the Jump MD System are shown in Table 2. The quadriceps femoris muscle strength and one-legged vertical jumping ability for the dominant side in the healthy subjects and the involved and uninvolved sides in the ACL-R patients are shown in Fig. 4.

Table 2. ICC (1.1) values describing the reliability of the variables measured for the one-legged vertical jumps by the MYOTEST System and the Jump MD System.

	Power	Force	Velocity	Height
ICC(1.1)	0.87	0.82	0.83	0.89

Power was defined as the ability to exert force quickly
Force was the extension strength of lower extremity
Velocity was the vertical velocity of one legged vertical jumping
Height was the height of one legged vertical jumping

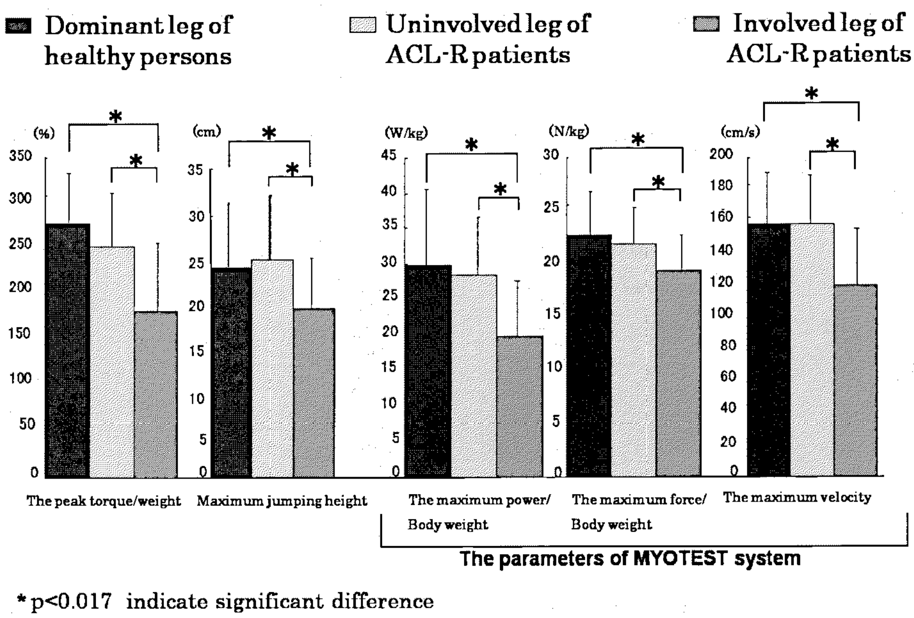

Fig. 4. Comparisons of the quadriceps strength and the one-legged vertical jumping ability between the dominant side in the healthy subjects and the involved and uninvolved sides in the ACL-R patients.

The maximum quadriceps strength, jumping height, power, force and velocity were 277.8 ± 54.8%, 23.0 ± 6.4 cm, 29.8 ± 10.7 W/kg, 22.6 ± 4.1 N/kg and 158.0 ± 31.6 cm/s, respectively, for the dominant side in the healthy subjects. In the ACL-R patients, the corresponding values were 252.5 ± 57.9%, 23.8 ± 5.9 cm, 28.4 ± 8.2 W/kg, 21.8 ± 3.3 N/kg and 157.2 ± 31.5 cm/s, respectively, for the uninvolved side and 181.5 ± 74.0%, 18.5 ± 6.1 cm, 19.8 ± 7.9 W/kg, 19.3 ± 3.3 N/kg and 119.1 ± 35.5 cm/s, respectively, for the involved side.

In the ACL-R patients, the differences in all parameters between the involved and uninvolved sides were statistically significant ($p < 0.017$). There were no significant differences in any of the parameters between the dominant side in the healthy subjects and the uninvolved side in the ACL-R patients. The differences between all the parameters on the dominant side in the healthy subjects and the involved side in the ACL-R patients were statistically significant ($p < 0.017$).

The relationships between the maximum jumping height and the maximum power, force and velocity for the dominant side in the healthy subjects and the involved and uninvolved sides of the ACL-R patients are shown in Table 3.

Table 3. Pearson's product moment correlation values describing the relationships between the maximum jumping height and the maximum power, force and velocity for the dominant side in the healthy subjects and the involved and uninvolved sides in the ACL-R patients.

	Power	Force	Velocity
Height of dominant side	0.31	0.61**	0.04
Height of uninvolved side	0.43*	0.43*	0.38*
Height of involved side	0.46**	0.35*	0.58**

*$p < 0.05$ and **$p < 0.01$ indicate significant correlation
Dominant side was the leg usually used for kicking a soccer ball
Involved side was the anterior cruciate ligament reconstruction (ACL-R) leg
Uninvolved side was the leg that had no history of surgery or traumatic injury

Discussion

Several authors have reported a deficit in the quadriceps femoris strength at 60 deg/s compared with the uninvolved side after ACL-R[9,16,17]. Based on these studies, we measured the quadriceps femoris strength at 60 deg/s. Gustavsson et al.[3] reported that there were no side-to-side differences in healthy subjects, but significant differences between the involved and uninvolved sides in ACL-R patients. In the present study, all the healthy subjects had the right side as their dominant side. Therefore, the dominant sides were adopted to unify the tested sides.

The authors measured the maximum power, force and velocity during one-legged vertical jumps including the jumping height. A reproducibility coefficient of 0.80 or higher is considered "acceptable" in most social science applications[18]. In the present study, the ICC values of all the parameters were above 0.80, indicating that the measurements of the height, power, force and velocity obtained in the study were reproducible.

The movement of a one-legged vertical jump is generated by hip extension via the gluteus maximus muscle and the hamstrings, knee extension via the quadriceps femoris and ankle plantar-flexion via the gastrocnemius-soleus complex. The subjects were asked to jump as high as possible. The hip or ankle extensors may compensate for a knee extension moment deficit during the performance of a vertical jump[19]. Furthermore, the hip extensor is the main contributor to the vertical velocity because it increases the vertical velocity of the hips[14]. To attain the maximum jumping height, the patients could change their jumping strategy to create a higher velocity. Presumably, the jumping height and the velocity are related when a hip or an ankle extensor strategy is used predominantly rather than a knee extensor strategy.

Only the maximum force was correlated with the maximum jumping height for the dominant side in the healthy subjects. The healthy subjects can make use of stronger force to attain the maximum jumping height. It can be considered that the velocity cannot be increased while excessive force is used. This must give strong influence to the power.

The maximum quadriceps femoris strength for the involved side in the ACL-R patients was 65.3% of that for the dominant side in the healthy subjects. Despite rehabilitation, persistent quadriceps femoris weakness seems to be common in the ACL-injured leg and the muscle function can continue to improve for up to 18 months after ACL-R[16]. The maximum height, power, force and velocity during one-legged vertical jumps for the involved leg in the ACL-R patients were 80.4%, 66.4%, 86.1% and 75.4%, respectively, of those of the dominant side in the healthy subjects. The times to attain the maximum power, force and velocity were different during the one-legged vertical jumps. Compensation from the hip or ankle extensors during one-legged vertical jumps can lead to higher values for the jumping height, velocity and force. However, the power cannot attain a higher value because of the influence of the force or velocity. The lower cooperation in ACL-R patients may also influence the power during one-legged vertical jumps. Therefore, the maximum power may be a better index for the assessment of jumping ability after ACL-R.

The patients were evaluated at 6 to 12 months after ACL-R. It can be considered that the muscle strengths differed between 6 and 12 months after ACL-R. In addition, the patients were not classified or excluded depending on their level of rehabilitation success or muscle strength. These aspects may have influenced the results. In the future, the patients should be divided by their muscle strength and the maximum power, force and velocity during one-legged vertical jumping tests should be compared.

In the present study, the authors analyzed the kinetic aspects of one-legged vertical jumps. A different jumping strategy may explain the difference in the correlations between the maximum jumping height and the maximum power, force and velocity during one-legged vertical jumping tests for the involved and uninvolved sides in the ACL-R patients and the dominant side in the healthy subjects. The present findings indicate the importance of a knee strategy during one-legged vertical jumps for rehabilitation. Moreover, the assessment of jumping ability after ACL-R may be determined by the maximum power instead of the maximum jumping height. These data can improve our prediction of postoperative recovery and thereby guide our instructions and approach to postoperative rehabilitation.

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