Kinetic chain weight training, strength assessment, and functional performance testing

With reference to sports and rehabilitation

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BODY BUILDING EXPRESSION
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Abstract. The overall purpose of the studies was to obtain knowledge about physical performance in healthy individuals and patients after anterior cruciate ligament (ACL) reconstruction. Data are presented that concerns closed and open kinetic chain exercise, adaptive response to weight training, the methodology of muscle strength assessment, and the development of a functional testing protocol performed under conditions of fatigue.

Study I: The purpose of this study was to compare the effect of closed versus open kinetic chain weight training of the thigh muscles. Healthy subjects performed closed (n=12) and open (n=12) kinetic chain weight training twice a week for six weeks. Both groups increased in a barbell squat test, although the closed kinetic chain group improved more than the open kinetic chain group. The closed kinetic chain group improved their jumping ability, however, there was no difference across groups. Large improvements in isotonic strength in both groups did not transfer to an isokinetic knee-extension test.

Study II: The purpose of this study was to investigate the ability of closed and open kinetic chain strength tests to assess functional performance in 16 healthy male subjects. Moderately strong correlations were found between a barbell squat test, an isokinetic knee-extension test, and a vertical jump test. It is suggested that the effect of training or rehabilitation interventions should not be based exclusively on tests of muscular strength. Instead, various forms of dynamometry including functional performance tests could be recommended.

Study III: The purpose of this study was to investigate the effect of “pre-exhaustion” exercise (knee-extension) on lower-extremity muscle activation during a leg press exercise. Seventeen healthy male subjects performed one set of a leg press exercise with and without pre-exhaustion. The electromyography activation of the vastus lateralis and the rectus femoris muscles was less when pre-exhausted. Our findings do not support the popular belief that performing pre-exhaustion exercise more effectively enhances muscle activity compared with regular weight training.

Study IV: A pre-exhaustion exercise protocol was combined with single-leg hop testing to improve the possibilities to evaluate the effects of training or rehabilitation interventions. High test-retest reliability was noted for 11 healthy male subjects performing non-fatigued and fatigued hop testing. Additionally, we investigated how fatigue influences lower-extremity joint kinematics and kinetics during single-leg hops. Absorbed power during landing was two to three times greater for the knee than for the hip and five to ten times greater for the knee than for the ankle across test conditions.

Study V: A new hop test, performed under conditions of fatigue, was investigated to determine functional deficits after ACL reconstruction. Although no patients (n=19) displayed abnormal hop symmetry when non-fatigued, two thirds showed abnormal hop symmetry for the fatigued hop condition. It is concluded that a fatigued exercise protocol combined with the single-leg hop test improved testing sensitivity when evaluating lower-extremity function after ACL reconstruction.

Conclusions: Although strength measurements are important to monitor the effect of training and rehabilitation interventions, they cannot fully assess functional performance. Functional deficits after ACL reconstruction may become more apparent during conditions of fatigue. For a more comprehensive evaluation of lower-extremity function after ACL reconstruction, it is therefore suggested that functional testing should be performed under both non-fatigued and fatigued test conditions.

Key words: open kinetic chain, closed kinetic chain, weight training, strength assessment, functional tests, anterior cruciate ligament, reconstruction, fatigue
List of papers

The present thesis is based on the following papers, which will be referred to in the text by their Roman numerals.


In the present thesis, the following abbreviations and definitions were used.

**ACL.** Anterior cruciate ligament.

**Closed kinetic chain.** Weight-bearing movement or exercise that involves muscles working across multiple joints (a barbell squat exercise, for example).

**Concentric muscle action.** When the muscle shortens while producing force.

**Dynamic muscle action.** Involving either an increase or decrease in joint angles.

**Eccentric muscle action.** When a muscle lengthens while producing force.

**EMG.** Electromyography.

**ICC.** Intraclass correlation coefficient.

**Isokinetic muscle action.** Refers to a muscle action performed at a constant angular joint velocity. Unlike other types of weight training, there is no specified resistance to meet; rather, the velocity of movement is controlled. The resistance offered by an isokinetic dynamometer cannot be accelerated; any force applied against the machine results in an equal reaction force.

**Isometric muscle action.** When a muscle is activated and develops force but no movement at a joint occurs, an isometric muscle action takes place.

**Isotonic muscle action.** Refers to an exercise performed at a variable speed with fixed resistance. The term isotonic (iso + tonic = same tension) implies constant tension. The execution of free weight and weight machine exercises is usually regarded as isotonic; however, dynamic action of a muscle in exercise and sports hardly ever involves constant force development. As a result, the term ‘isotonic’, implying uniform force throughout a dynamic muscle action, has therefore been considered inappropriate (Knuttgen and Komi 1992).

**Kinematics.** The study of movements which describes the motion of a joint.

**Kinetics.** Static and dynamic analysis of the forces and moments acting on a joint.

**MVIA.** Maximal voluntary isometric activation.

**Nm.** Newton meter.

**Open kinetic chain.** Non-weight-bearing movement or exercise that involves muscles working across only single joints (a weight machine knee-extension exercise, for example).

**Power.** Power is the rate of performing work; the product of force and velocity (SI unit: Watt). Power during a repetition is defined as the weight lifted multiplied by the vertical distance the weight is lifted divided by the time it takes to complete the repetition.
**Power absorption.** The ability of the muscle to perform work (negative power) during the eccentric phase of a movement. Absorbed power of the quadriceps muscle, for example, occurs when walking down stairs.

**Power generation.** The ability of the muscle to perform work (positive power) during the concentric phase of a movement. Generated power of the quadriceps muscle, for example, occurs when walking up stairs.

**Repetition maximum (RM).** This is the maximum number of repetitions per set that can be performed until failure at a given resistance using a proper exercise technique. So, a set at a certain RM implies that the set is performed to momentary voluntary fatigue. 1 RM is the heaviest resistance that can be lifted for one complete repetition of an exercise. 8 RM, for example, is a lighter resistance that allows completion of eight, but not nine, repetitions using a proper exercise technique.

**Repetition.** A repetition is one (complete) movement of an exercise. It normally consists of two phases: the concentric muscle action, in which the muscle shortens, and the eccentric muscle action, in which the muscle lengthens.

**SD.** Standard deviation.

**SEM.** Standard error of the mean.

**Set.** This is a group of repetitions normally performed continuously without stopping. While a set can be made up of any number of repetitions, sets during weight training typically range from one to 20 repetitions.

**Strength.** Strength is the maximal amount of force a muscle or muscle group can generate in a specified movement pattern at a specified velocity (including an isometric muscle action) of movement.

**Stretch-shortening cycle.** A common pattern of muscle activation in everyday activity and athletic competition is to combine eccentric and concentric activations. Such sequencing of muscle action is termed a stretch-shortening cycle.

**Weight training.** The terms resistance, weight, and strength training have all been used to describe a type of exercise that requires the body’s musculature to move (or attempt to move) against an opposing force, usually presented by some type of equipment. The terms resistance and strength training encompasses a wide range of training modalities, including plyometrics (drop jumps, for example) and hill running. Weight training, on the other hand, is typically used to refer only to training using free weights, such as barbells and dumb-bells, or weight machines.
Introduction

Weight training: brief history
The human ability to generate muscle force has fascinated mankind throughout most of recorded history. A 140 kg block of red sandstone found in Olympia had a 6th-century inscription stating that the weight lifter Bybon, using only one hand, had lifted it over his head. The Greek athlete Milos of Crotona has been credited with the first use of progressive resistance exercise. It is reported that he lifted a bull-calf every day until it was fully grown, and that he was eventually able to carry the bull around the stadium at Olympia (Fry et al. 2002b). Records indicated that Galen (A.D. 129–199), considered the most outstanding physician since Hippocrates in ancient times, classified exercises into those that exercised the muscles without violent movement (e.g. digging, weightlifting), quick exercises that promote activity (e.g. ball play, rolling on the ground), and violent exercises (Gardiner 1930). The 19th and early 20th century was the era of the strongmen in Europe and North America (Fry et al. 2002b). Canadian strongman Louis Cyr (1863-1912) is possibly the strongest man who ever lived. He might have performed the greatest strength feat in history when he once lifted a platform carrying eighteen men, a total of more than 2000 kg, on his back. In 1886, Louis Cyr set a record by lifting up a weight of 251 kg using just the middle finger of his right hand. The strongest woman in the world (relative to body mass) is arguably power lifter Carrie Boudreau of the United States, who is the current world record holder in the 56-kg weight class with a 222.5 kg dead lift (Vanderburgh and Dooman 2000). In the 1940s, research into the field of strength training increased, with investigators experimenting with more precise training prescriptions. Pioneers of strength research include Thomas L. De Lorme and Peter V. Karpovich, who wrote the first science-based articles and books on the subject of strength training (De Lorme and Watkins 1948; Murray and Karpovich 1956). This work is thought to have revolutionised the field of training athletes and was also adopted as textbooks in many physical education classes (Todd and Todd 2003). In 1946, De Lorme developed an exercise strategy based on the notion that muscles should be tested when exerting “maximum effort”. To make his idea applicable to clinical settings his exercise programmes were based on a single maximal contraction of muscles through the full range of motion. He called this maximum effort the “one repetition maximum” or 1 RM (De Lorme 1946).

Traditionally, weight training was limited to sports like power lifting, body building, and Olympic weightlifting. More recently, however, the pursuit of sporting achievement has resulted in the increased use of weight training by other athletes to enhance sporting performance. In fact, sports that do not utilise
resistance training have become the exception rather than the rule (Kraemer et al. 2002).

**Benefits of weight training**

Weight training impacts several body systems, including the muscular, endocrine, skeletal, metabolic, immune, neural, and respiratory systems (Deschenes and Kraemer 2002). Trainable fitness characteristics when performing weight training include muscular strength, power, hypertrophy, and local muscular endurance. Other variables such as speed, balance, co-ordination, jumping ability, flexibility, and other measures of motor performance have also been positively enhanced (Colliander and Tesch 1990; Delecluse et al. 1995; Rutherford and Jones 1986; Stone et al. 1981; Thrash and Kelley 1987).

Resistance training has become increasingly popular in the general population, and it is regarded as the most effective method available for maintaining and increasing lean body mass and improving muscular strength and endurance in healthy populations (Hass et al. 2001). The benefits for elderly individuals of regular participation in resistance-training programmes include improvements in bone density, muscle mass, arterial compliance and energy metabolism, which may offset age-, inactivity- and disease/disability-associated declines in functional capacity (Mazzeo and Tanaka 2001). Moreover, resistance training has proven effective for the prevention and rehabilitation of orthopaedic injuries (Feigenbaum and Pollock 1999). Further, participation in exercise programmes incorporating resistance training has been shown to reduce the risk of several chronic diseases (coronary heart disease, obesity, diabetes mellitus, and osteoporosis, for example) (Hass et al. 2001).

**Intensity (load)**

The intensity of the exercise (i.e. the amount of resistance used) is arguably the most important variable in weight training (Kraemer et al. 1998). The intensity of an exercise can be estimated as a percentage of the 1 RM or any RM for the exercise. The minimal intensity that can be used to perform a set to momentary voluntary fatigue to result in increased strength is still unclear. Traditionally, loads of less than 60% of 1 RM have been considered insufficient and resulting in no strength gains (McDonagh and Davies 1984). At least 80% of 1 RM is thought to be needed to produce any further strength increases in experienced lifters (Häkkinen et al. 1985). However, Takarada and Ischii (2002a) investigated the effects of weight training with low intensity (50% of 1RM) and a short interset rest period (30 seconds). The results showed considerable effects of the exercise regimen that, in spite of its low intensity, had a considerable effect in inducing muscular hypertrophy and a concomitant increase in strength. Rhea et al. (2003) carried out a meta-analysis of 140 weight training studies to identify the magnitude of strength gains along the continuum of training
intensities. It was concluded that training with a mean intensity of 60% of 1 RM elicits maximal gains in untrained individuals, whereas 80% is most effective in those who are trained. In power lifting, however, where the principal training goal is to optimise maximal strength, training is rarely carried out using loads below 90% of 1 RM (Fleck and Kraemer 1997).

It has recently been reported that low-intensity (30-50% of 1 RM) resistance training, combined with moderate vascular occlusion, produced gains in strength that were greater than those produced by low-intensity resistance training alone and were comparable to those achieved after conventional high-intensity resistance training (Shinohara et al. 1998; Takarada et al. 2000a; Takarada et al. 2002b).

Taken together, the optimal training intensity to achieve maximal gains in strength and muscle volume, assuming that an optimal intensity actually exists, remains unclear.

Training volume
Training volume is a summation of the total number of repetitions and sets performed during a training session multiplied by the resistance used. A change in training volume can be accomplished by changing the number of exercises performed per session, the number of repetitions performed per set, or the number of sets per exercise. The relationship between training volume and muscular hypertrophy is not clear. However, some authors claim that a relationship exists, as body builders, who often use large training volumes, develop large muscles (Fleck and Kraemer 1997). Studies using two or more sets per exercise have all produced significant increases in muscular strength in both trained and untrained individuals (Dudley and Djamil 1985; Staron et al. 1994; Hortobagyi et al. 1996; Housh et al. 1992).

One aspect of training volume that has recently received considerable attention is the comparison of single- and multiple-set resistance training programmes (i.e. the number of sets completed of each exercise) (Carpinelli and Otto 1998; Feigenbaum and Pollock 1999; Hass et al. 2000; Kraemer et al. 2002; McBride et al. 2003; Paulsen et al. 2003, Rhea et al. 2003). The proponents of single-set programmes conclude that they elicit similar gains in strength and hypertrophy as multiple sets (Carpinelli and Otto 1998; Feigenbaum and Pollock 1999; Hass et al. 2000). Further, single-set programmes are regarded as less time consuming and more cost efficient, which may translate into improved programme compliance, e.g. during rehabilitation of orthopaedic injuries (Feigenbaum and Pollock 1999). Supporters of multiple sets, on the other hand, claim that trained subjects are clearly dependent on multiple sets to ensure strength progress and hypertrophy (Kraemer et al. 2002; McBride et al. 2003; Paulsen et al. 2003, Rhea et al. 2003). At present, there is no clear consensus on this topic, and there appears to be a need for studies in
which this topic is further explored in different ways (e.g. untrained versus trained subjects, short-term versus long-term adaptations, periodised versus non-periodised training, and small muscle groups versus large muscle groups).

Rest between sets
This acute training variable can be manipulated to provide great variety in the metabolic characteristics of the training session. Training intensity is affected by the rest intervals, so these variables are related. When high power activities or high load exercises are performed, long rest intervals (e.g. 3-5 minutes) are often used to allow adequate recovery before subsequent sets are performed (Fry et al. 2002a). When maximal hypertrophy is the main training goal, exercises are often performed to muscular exhaustion, and rest intervals between sets are very short (e.g. 30 to 60 seconds). Methods such as pre-exhaustion exercise, in which two different exercises are performed without any rest between them, are also often used by weight trainers when hypertrophy is desired (Augustsson et al. 2003).

However, the effects of fatigue on muscle function and the implications of this in terms of strength and muscle hypertrophy acquisition are not well documented and existing data relating to whether fatigue may stimulate strength and muscle volume development are contradictory. Rooney et al. (1994) reported that fatiguing, continuous repetitions resulted in greater strength gains compared with when rest was taken between repetitions. Similarly, Schott et al. (1995) demonstrated greater strength gains and muscle hypertrophy following strength training using long, fatiguing activations compared with short, intermittent activations. Conversely, Pincivero et al. (1997b) examined the influence of rest intervals on strength gains subsequent to high-intensity training and reported that a longer rest period between sets resulted in a greater improvement in muscle strength. The results obtained by Pincivero et al. (1997b) are supported by the observation that the development of fatigue is not desirable in power lifting, where the principal training goal is to optimise maximal strength (Fleck and Kraemer 1997).

Taken together, it is not clear whether the duration of the rest intervals between sets is of importance if the objective is to bring about maximal muscle hypertrophy and strength gains.

Frequency
The optimal training frequency (the number of workouts per week) may depend on several factors such as training volume, intensity, exercise selection, training status, recovery ability, and the number of muscle groups trained per workout session (Kraemer et al. 2002).

The frequency of training appears to differ by training status. In untrained individuals, a consistent dose-response was noted, as the number of days each muscle group was trained increased up to three days a week. For trained
individuals, two days a week elicited the greatest strength increases (Rhea et al. 2003). Unfortunately, the effect of training each muscle group on only one day a week in trained individuals was not investigated. However, training each muscle group only once a week (or even more infrequently) is common practice among experienced weight trainers (Augustsson 2002), and this approach requires further scientific study.

Increasing training frequency may enable greater specialisation (e.g. greater exercise selection and volume per muscle group in accordance with more specific goals). Performing upper-body exercises during one workout and lower-body exercises during a separate workout (upper/lower-body split) or training specific muscle groups (split routines) during a workout are common at advanced levels of training in addition to total-body workouts. For those individuals desiring a change in training structure (e.g. upper/lower-body split, split workout), an overall frequency of three to four days a week has been recommended, so that each muscle group is only trained one or two days a week (Fleck and Kraemer 1997). However, the optimal frequency necessary for progression during advanced split-routine training remains unknown.

Free weights versus machines
The Swedish physician and scientist Gustaf Zander is sometimes credited with being the first inventor and manufacturer of weight training machines, in the 1860s (Söderberg 1999) (Figure 1). Therapists, coaches and athletes design and implement resistance-training programmes that involve both free weights and weight machines. These programmes are often designed in an attempt to improve strength, power, and ultimately athletic and functional performance. The pros and cons of training with free weights versus weight machines are widely discussed, both among athletes and coaches, among physical therapists and in sports science. Differences of opinions exist as to which method would result in optimal performance gains.

The proponents of free weights (barbells and dumb-bells) feel that they are versatile, require balance and co-ordination, much like actual sporting events, allow for small incremental adjustments in resistance, and allow for multiplanar movements compared with weight machines. The believed disadvantages of free weights are that some movements (bench press, squats and so on) require spotters or special racks; and they may also be psychologically intimidating to some novice trainees. Moreover, several body movements are difficult to exercise with free weights. One example would be torso transverse rotation, which is important for combative sports such as wrestling and judo, for example (Haff 2000).

The general advantages of resistance exercise machines are thought to be that they do not usually intimidate novice users; they can be designed to provide resistance in any direction; do not generally require a spotter for safety; they are
less likely than free weights to cause injury to a user who is inept or careless; and they may be organised in a circuit to provide a fast and convenient way to exercise all major muscle groups. The believed disadvantages of resistance exercise machines are that they generally provide for the sequential training of isolated muscle groups rather than training major muscle groups in unison and that they do not usually lend themselves to ballistic or “explosive” exercises such as weighted jumps (Haff 2000).

Finally, although there are theoretical advantages and disadvantages to free weights and weight machines, there is no strong scientific evidence to support the superiority of one modality over the other. For example, perhaps more balance and coordination are required to perform free weight exercises compared with machine exercises, but there is no evidence that this skill has any significant transfer to other activities, such as running, jumping or throwing. In accordance, we compared six weeks of free weight with weight machine training for the lower-extremities and found that there were no differences across groups in a vertical jump test (Augustsson et al. 1998).

Figure 1. Picture of the Swedish physician and scientist Gustav Zander in 1865, here seen performing “biceps curls” in his self-invented weight training machine (Photo: Swedish Museum of Science and Technology, Stockholm, Sweden).
Strength assessment
Ancient cultures utilised tests of muscular strength for both entertainment and utilitarian purposes. For example, strength tests were being used for military purposes as early as during the Chou dynasty in China (1122-255 BC) (Fry et al. 2002b). More recently, various dynamometers (e.g. for assessment of grip strength) were developed and adopted by neurologists in the late 19th century to measure muscle strength, in keeping with the general trend at that time of adopting instrumentation to distinguish and aid observation and diagnosis (Lanska 2000).

Purposes of assessment
Tests of muscular strength and power are commonly performed to assess functional performance, in both the sporting and the rehabilitation fields. Monitoring strength performance may be useful for many groups of individuals, ranging from the high-velocity power testing of the elite athlete to the ability of an elderly individual to rise from a chair. According to Abernethy et al. (1995), strength and power are assessed for four main purposes: 1) to quantify the relative significance of strength and power to various athletic events and tasks; 2) to identify the specific deficiencies in muscular function to improve individual deficiencies (i.e. strength diagnosis); 3) to identify individuals who may be suited to particular athletic pursuits (i.e. talent identification) and 4) to monitor the effects of training or rehabilitation interventions.

Dynamometry
Currently, methods of strength assessment fall into three main categories—isometric, isokinetic and isotonic testing (Abernethy et al. 1995). Isometric strength is the maximal voluntary muscle activation that can be developed against an immovable object, without a change in joint angle. Often both the maximum force and the rate of force development are recorded. Isokinetic assessments involve the measurement of torque and power through a range of motion in which the limb is moving at a constant angular velocity. Maximal isotonic strength (i.e. the 1 RM) is often used as a measure of strength for athletic profiling and is regarded by some as the “gold standard” of dynamic strength testing (Franklin 2000).

Each method is considered to have drawbacks, the main argument against isometric assessment being that isometric tests bear little resemblance to the dynamic nature of most sporting activities (Wilson and Murphy 1996). The perceived disadvantage of isokinetic assessment is the absence of acceleration and stretch-shortening cycle, and that single joint, isolated assessments, such as seated knee-extensions, are often used, even though they bear little resemblance to functional performance (Fry et al. 1991; Sleivert et al. 1995; Wilson et al. 1993). Those opposed to isotonic assessment tend to emphasise poor reliability...
and objectivity due to inter-subject, inter-trial and inter-laboratory variations (Abernethy et al. 1995).

Reliability of different forms of dynamometry
Ideally, all sports medicine procedures should be reliable. A threat to the reliability of strength tests is the proximity of the assessment to previous training sessions. The time it takes to recover isotonic, isometric and isokinetic strength after an intensive bout of weight training or strength testing is far from well investigated (Abernethy et al. 1995; Michaut et al. 2003). Moreover, the effect of endurance training prior to strength assessment has not been sufficiently studied. The recommended time that the physical activity of healthy subjects or patients should be limited prior to strength assessment is therefore unclear.

Isometric dynamometry
Isometric assessment techniques generally present high test-retest reliability (Blazevich et al. 2002; Chiu and Sing 2002; Meldrum et al. 2003; Wilson et al. 1993). However, reliability coefficients may vary depending on several factors. For instance, Agre et al. (1987) reported poorer reliability coefficients for lower-limb (0.20 to 0.96) than for upper-limb (0.85 to 0.99) isometric strength testing. Moreover, work by Christ et al. (1994) indicates that reliability varies between muscle groups. The ICCs for the maximal voluntary isometric activation of dorsiflexors and forearm extensors were 0.55 and 0.64, respectively, while the coefficients were 0.94 and 0.91 for the plantar and forearm flexors.

Isometric tests usually involve participants producing a maximal force against an immovable resistance, which is in series with a strain gauge, cable tensiometer, force platform or similar device whose transducer measures the applied force (Wilson and Murphy 1996). However, we have developed a new method for measuring maximal isometric muscle strength, using a conventional weight training machine (M. Bruno et al. unpublished work) (Figure 2). This isometric test showed high test-retest reliability for both women ($r=0.94$) and men ($r=0.99$).

Isokinetic dynamometry
Generally, the test-retest reliability of isokinetic tests is high. Research groups have reported high reliability coefficients (>0.90) for several isokinetic devices, including the Kin-Com, the Cybex and the Biodex system (Wilk 1990). Reliability, however, decreases as the contractile speed increases (Oesternig 1986). Although the reliability coefficients for eccentric muscle actions appear to be slightly less than those for concentric muscle actions, they remain high ($r>0.90$) (Seger et al. 1988).
Isotonic dynamometry
The observed test-retest reliability of 1 RM measurements amongst experienced male and female weight trainers is high ($r=0.91$ to 0.98) (Hortobagyi et al. 1989; Hennessey and Watson 1994; Hoeger et al. 1990; M. Bruno et al. unpublished work). More dynamic tests, such as the weighted squat jump, appear to be equally reliable; for example, Stone et al. (2003) reported high test-retest reliability for a weighted squat-jump test (ICC=0.88).

Correlations between strength measures and functional performance
The number of published studies correlating tests of strength with functional performance is limited in the literature. This is somewhat surprising, as this kind of information allows us to determine the relationship a particular test of strength has with running, jumping or throwing, for example. In cases where there are meaningful correlations it is, for example, possible to determine

Figure 2. The principle for determining maximal isometric strength, using a conventional weight training machine. As the subject performed a muscle action that dislodged a particular test weight, a cord attached to a free-weight plate fell out of the weight stack and the trial was considered successful. The weight lifted was incremented by 2.5-10 kg until the subject failed to dislodge the test weight within five seconds (M. Bruno et al. unpublished work).
whether differences in strength discriminate between levels of performance and whether training and rehabilitation interventions affect strength measures.

It is currently not clear when an individual is regarded as fully rehabilitated and fit for full sports participation (Murphy et al. 2003; Parkkari et al. 2001). It is also not known whether strength tests can be used to predict future performance, and thereby, reduce the risk of re-injury, for example, when an individual returns to sport following rehabilitation. More detailed studies are therefore needed about the risk of re-injury, when individuals with reduced leg strength return to sports participation after anterior cruciate ligament (ACL) reconstruction, for example. In knee rehabilitation literature, the vast majority of studies show persisting side-to-side differences in thigh muscle strength after ACL reconstruction (Anderson et al. 2002; Arangio et al. 1997; Carter and Edinger 1999; Ernst et al. 2000; Hiemstra et al. 2000; Keays et al. 2003; Lewek et al. 2002; Mattacola et al. 2002; Pfeifer and Banzer 1999; Risberg et al. 1999; Urbach et al. 2001; Wojtys and Huston 2000). In ACL rehabilitation, protocols are often used in which a recommended minimum leg muscle strength must be achieved corresponding to 85 or 90%, for example, compared with the non-operated limb, before no restrictions are needed be taken in sport and work activities (Østerås et al. 1998). However, the relationship between tests of muscular function and functional performance is still not clear. Recent studies, however, indicate a relatively low relationship between tests of muscle function and dynamic performance, both in healthy subjects (Murphy and Wilson 1997; Wilson et al. 1997) and in subjects with ACL-reconstruction (Pfeifer and Banzer 1999). Pincivero et al. (1997a) studied the relationship between concentric isokinetic quadriceps and hamstring strength values with the single-leg hop for distance, a functional activity. It was concluded that only low to moderate relationships existed between the single-leg hop and the knee strength tests.

Although the degree of difference in strength performance between the two lower-extremities has not been shown to have a definite relationship with a propensity towards injury during athletic activities (Williams et al. 2001), a difference of 10% or more can be considered to reflect a real difference in the capacity of performance (Sapega 1990). Taken together, our research group regard a side-to-side difference of more than 10% between the involved and non-involved leg following ACL reconstruction as unsatisfactory for strength test scores, and believe that it may predispose an individual to overuse and/or acute injuries when returning to sports or strenuous work.

**Sensitivity of different tests to the effects of training or rehabilitation**

One important issue is whether isometric, isotonic and isokinetic tests are sensitive to the effects of various training and rehabilitation regimens; and whether these tests are similarly sensitive to the effects of training and rehabilitation.
According to several studies (Augustsson et al. 1998; Sleivert et al. 1995; Wilson et al. 1993), isokinetic tests are not sensitive to isotonic weight training strength improvements. The rationale for performing isokinetic tests in clinical practice is therefore somewhat weak, as weight training during rehabilitation is typically performed using free weights and weight machines in an isotonic mode alone. Murphy and Wilson (1997) examined the ability of isokinetic and isotonic tests of muscular function to track weight training-induced changes in performance. The results showed that weight training (barbell squats) significantly enhanced sprint time. However, apart from the squat, no measure of muscular function significantly changed because of training. Murphy and Wilson (1997) therefore suggested that tests of muscular function cannot be used to monitor training-induced changes in performance, and that the effectiveness of training should be based on changes in performance rather than changes in test scores of muscle function. However, the restoring of muscle size and strength is a cornerstone of rehabilitation; and tests of muscular function must therefore be regarded as important (Augustsson and Thomeé 2000).
Closed and open kinetic chain

Definitions
The terms “closed kinetic chain” and “open kinetic chain” have gained considerable attention in the field of rehabilitation in recent years. A closed kinetic chain exercise involves muscles working across multiple joints, whereas an open kinetic chain exercise uses muscles working across only single joints. Moreover, in an open kinetic chain, the distal segment terminates free in space, whereas, in a closed kinetic chain, the distal segment is fixed (Brunnstrom 1983). A barbell squat is a free weight, closed kinetic chain exercise, involving muscles working across multiple joints. Athletes, using resistance training, often include the barbell squat exercise into their programmes to improve lower-extremity strength. Several studies have used a barbell squat test to determine the effect of various training and rehabilitation interventions (Hickson et al. 1994; Wilson et al. 1997). Isokinetic or isotonic testing and training such as weight machine knee-extension/flexion, using muscles working across only single joints in an open kinetic chain, are also commonly used to evaluate and improve lower-extremity strength (Fry et al. 1991; Thomeé et al. 1995) (Figure 3).

Figure 3. A barbell squat is a free weight, closed kinetic chain exercise, involving muscles working across multiple joints (left picture). The weight machine knee-extension exercise involves muscles working across a single joint in an open kinetic chain (right picture). Photos by Roland Thomeé and Marko Ervasti.
Biomechanical studies
In sports medicine literature, there is currently a preference for closed kinetic chain exercises, based on the assumption that these exercises more closely approximate functional activities, such as running or jumping (Lutz et al. 1993; Wilk et al. 1996). Additionally, it is believed that the strain that some open kinetic chain exercises place on the maturing graft may adversely affect the long-term stability of the reconstructed knee (Bynum et al. 1995; Yack et al. 1993). Biomechanical, electromyographic, and strain gauge studies have been used to compare closed and open kinetic chain exercises. In response, some authors have recommended the exclusive use of closed kinetic chain exercise and the exclusion of traditional open kinetic chain exercise (Bynum et al. 1995; Kvist and Gillquist 2001). It has been concluded, however, that both types of exercises can be performed in ways that do not place excessive strain on the ACL (Fitzgerald 1997). When comparing knee joint biomechanics during closed and open kinetic chain weight training at a 12 RM load, Escamilla et al. (1998) reported that peak ACL tension forces in open kinetic chain exercise were 0.2 times body weight, and non-existent in closed kinetic chain exercise (Figure 4). Fleming et al. (2001), on the other hand, noted that weight-bearing (closed kinetic chain) exercise produced higher ACL strain values than non-weight-bearing (open kinetic chain) exercise.

![Figure 4. Escamilla et al. (1998) quantified knee forces in closed kinetic chain exercise (squat and leg press) and open kinetic chain exercise (knee-extension). Ten healthy male subjects performed three repetitions of each exercise at their 12 RM. Tension in the anterior cruciate ligament was present only in open kinetic chain exercise, and occurred near full extension (0.2 times body weight). Patellofemoral compressive force was greatest in closed kinetic chain exercise near full flexion and in the mid-range of the knee extending phase in open kinetic chain exercise (four to five times body weight).](image-url)
Factors such as joint compressive forces (e.g. axial loading) and joint geometry probably play integral roles in knee joint stability during closed kinetic chain exercise (Isear et al. 1997), whereas the significant co-activation of the antagonists during maximal knee flexion/extension, indicating an inhibitory mechanism which may prevent overloading of the joint and contribute to joint stabilisation (Kellis and Baltzopoulos 1998), would explain the low ACL tension forces during open kinetic chain exercise.

Taken together, only minor differences in ACL strain values have been reported when comparing closed and open kinetic chain exercises (Beynnon et al. 1997a). Further, despite numerous studies (Escamilla et al. 1998; Fleming et al. 2001; Kvist and Gillquist 2001; Wilk et al. 1996; Yack et al. 1993) of the biomechanics of the knee during closed and open kinetic chain exercises, the limits of strain that are safe for an uninjured or healing graft are currently still unknown (Beynnon et al. 2002).

**Testing**

Strength assessment for rehabilitation or sports purposes can be performed using either closed or open kinetic chain movement. However, few studies have compared the ability of closed and open kinetic chain tests of muscular strength to assess functional performance. In a study by Blackburn and Morrissey (1998), open kinetic chain knee extensor strength demonstrated very low correlation with vertical jump \((r=0.01)\) and standing long-jump \((r=0.07)\) performance, whereas Petschnig et al. (1998), who studied the relationship between an isokinetic quadriceps strength test and four different functional performance tests in healthy subjects and patients with surgery to the ACL, reported moderately strong correlation coefficients (between \(r=0.45\) and \(r=0.55\)). In a review (Abernethy et al. 1995) of articles in which correlations between muscular strength tests and functional performance were investigated, relationships typically ranged between \(r=0.50\) and \(r=0.93\). It is concluded that, although tests of strength are often used to monitor training-induced changes in performance or the effectiveness of rehabilitation, the relationship between tests of muscular function and functional performance is not clear.

In certain circumstances, both closed and open kinetic chain testing could be regarded as having low validity. As a diagnostic test, a closed kinetic chain movement, involving several groups of muscles working across multiple joints, is unable to determine the extent to which a particular muscle is activated (Salem et al. 2003). Conversely, the open kinetic chain test, because of its more “non-functional” nature, is able to isolate a specific muscle and thereby detect dysfunction. The purpose of assessment should therefore determine which mode of dynamometry that should used. To identify specific deficiencies or problem areas, open kinetic chain strength testing would be preferable, whereas a closed kinetic chain test may be better suited to assess functional performance.
Training
Quadriceps muscle hypotrophy and weakness frequently follows ACL injury and reconstruction (Anderson et al. 2002; Arangio et al. 1997; Carter and Edinger 1999; Ernst et al. 2000; Hiemstra et al. 2000; Keays et al. 2003; Lewek et al. 2002; Mattacola et al. 2002; Pfeifer and Banzer 1999; Risberg et al. 1999; Urbach et al. 2001; Wojtys and Huston 2000). Because this muscle is an important extensor and stabiliser of the knee joint, the restoration of quadriceps muscle mass and strength is regarded as paramount for successful ACL rehabilitation (Bodor 2001). Despite the importance of this muscle, however, there is currently no consensus regarding the optimal therapeutic prescription for restoring its function after ACL surgical repair. Therapeutic exercise selection has changed from the classical model (e.g. limited weight bearing, immobilisation, open kinetic chain exercises) (Johnson et al. 1992; Fu et al. 1992) to the current “aggressive” model emphasising early weight bearing, functional progression, and closed kinetic chain exercises (Beynnon 2002; Bynum et al. 1995).

Although effective ways of exercise training during rehabilitation following ACL reconstruction are still lacking, surprisingly few studies have attempted to compare the effect of different training regimes. However, Mikkelsen et al. (2001) conducted a prospective, randomised study that compared closed kinetic chain and combined closed and open kinetic chain rehabilitation initiated six weeks after ACL reconstruction. A six month follow-up revealed that the addition of open kinetic chain exercises produced a significant improvement in quadriceps strength, an earlier return to sport at the preinjury level, and did not affect measurements of anteroposterior knee laxity. The authors therefore recommended a combination of closed and open kinetic chain exercises to be used after ACL reconstruction, rather than performing only closed kinetic chain exercises.

The barbell squat exercise is a traditional closed kinetic chain exercise that has become an integral part of most lower-extremity strengthening and postoperative ACL rehabilitation programmes (Augustsson et al. 1998; Salem et al. 2003). The multiple-joint characteristics of a closed kinetic chain exercise such as the squat, however, may allow patients to use intra-limb substitution patterns that shift the effort from a targeted muscle group (e.g. knee extensors) to another muscle group (e.g. hip extensors) (Isear et al. 1997). Moreover, when these exercises are performed bilaterally, patients may shift the effort from the targeted limb (i.e. involved limb) to the contralateral limb. These substitution patterns may ultimately limit the effectiveness of the intervention exercise—preventing the correction of weakness in the involved limb (Salem et al. 2003). Additionally, strength training studies using closed kinetic chain exercises, but testing isolated quadriceps function alone, have found no statistically significant increases in quadriceps strength during open kinetic chain strength measures,
even though increases in strength were identified by using closed kinetic chain strength measures (Augustsson et al. 1998).

Taken together, these findings suggest that the exclusive use of closed kinetic chain exercises, for the purpose of reversing isolated quadriceps hypotrophy and dysfunction after ACL reconstruction, could be less effective compared with using both closed and open kinetic chain exercises.
**Functional performance testing**

During the rehabilitation of injuries to the lower-extremities, the assessment of the patient’s capacity is usually based on different scores, e.g. the Tegner activity score (Tegner and Lysholm 1985), on static measures (passive anterior tibiofemoral joint laxity, presence of pivot shift) (Sernert 2002), on the results of isokinetic strength measurements and often mainly on the subjective impression of the patient and the therapist (Pfeifer and Banzer 1999; Rudolph et al. 2000). Functional dynamic tests, however, are being used increasingly in the clinical setting and are recommended in sports medicine literature (Greenberger and Paterno 1995). These tests quantitatively measure (e.g. time, height, distance) the abilities of injured extremities and also provide information about the loading capacity in sport-specific situations, for example (Pfeifer and Banzer 1999).

**Types of functional tests**

Several types of functional tests (e.g. drop jump, figure-of-eight hop) have been investigated in order to try to identify the functional limitations of patients after ACL injury or reconstruction (Barber et al. 1990; Gauffin et al.1990; Itoh et al. 1998; Noyes et al. 1991; Tegner et al. 1986; Woodhouse et al. 1992). Among these, the hopping-type tests have been most commonly reported (Rudolph et al. 2000). Noyes et al. (1991) developed a series of hop tests to allow clinicians to compare the performance of the injured limb and the uninjured limb in persons with ACL deficiency. They reported that a side-to-side hop symmetry of less than 85% indicated diminished knee function that was related to quadriceps muscle weakness and patient self-assessment of difficulty with pivoting movements. Hop symmetry is now used as a standard measure of knee function in ACL-deficient and reconstructed individuals (Ageberg 2002). Hop tests have also been used to predict potential to succeed in non-surgical management and to advance patients to sport-specific rehabilitation activities following ACL reconstruction (Fitzgerald et al. 2000; Fitzgerald et al. 2001).

**Sensitivity of functional tests**

Researchers use single-leg hop tests to study knee function in ACL-deficient persons particularly because hopping is more challenging than walking or jogging and is thought by some to more closely represent the demands of high-level sports (Fitzgerald et al. 2000; Fitzgerald et al. 2001; Hefti et al. 1993; Noyes et al. 1991). However, the reported sensitivity of these tests in detecting functional limitations in ACL-deficient knees was relatively low, ranging from 38% to 58% (Noyes et al. 1991; Tegner et al. 1986). In order to accurately evaluate functional disability after ACL injury or reconstruction, it would be desirable to have a test with a higher sensitivity rate. Moreover, injuries often tend to occur at the end of a sporting event, when a participant is fatigued...
(Dugan and Frontera 2000, Feagin et al. 1987, Murphy et al. 2003; Östenberg and Roos 2000). However, it has been our observation that current functional tests, such as the single-leg hop, are typically performed under non-fatigued test conditions in both the clinical and the scientific setting. The ability of these tests to assess whether a patient has regained lower-extremity function after ACL reconstruction, for example, could therefore be regarded as limited. To improve the sensitivity of tests of lower-extremity function to evaluate the effect of rehabilitation interventions, the testing of dynamic function under fatigued conditions has therefore been suggested (Augustsson and Thomeé 2000). It could be hypothesised that performing single-leg hops under conditions of fatigue may be more sensitive in detecting functional impairment after ACL reconstruction, compared with traditional, non-fatigued hop testing.

Taken together, the sensitivity of dynamic tests in detecting functional limitations after ACL reconstruction should be a question for further study.
Rehabilitation after ACL reconstruction

Background
ACL injuries continue to be a source of major concern for athletes, researchers, and clinicians, due to their high incidence and long time for recovery (Fithian et al. 2002). It appears as if an ACL injury increases the risk for early development of osteoarthritis in the knee, regardless of whether ACL reconstruction is performed or not (Roos and Karlsson 1998).

Injury to the ACL may result in mechanical and functional instability. Athletes often find it difficult to return to full function after injury to the ACL, and surgery is frequently indicated (Fu et al. 2000). The long-term prognosis for sports participation after an ACL injury is uncertain, both after non-surgical treatment and after the reconstruction of the ruptured ligament (Beynnon et al. 2002; Roos and Karlsson 1998). However, the possibilities of a return to elite sports are illustrated by the fact that several players in the Swedish national soccer team, for example, have undergone ACL reconstruction. The literature on follow-up between five and 10 years after ACL reconstruction indicates that the incidence of revision ACL reconstruction ranges from 3 to 10% (Noyes and Barber-Westin 2001).

Postoperative rehabilitation
The surgical management of and rehabilitation programmes for ACL injuries have evolved during the last decade. In the past, the procedure was performed in an open fashion, frequently followed by several weeks of immobilisation. A return to sports a year or more postoperatively was considered the norm. Today, the procedure is routinely performed arthroscopically whereas rehabilitation has become more “aggressive”, including immediate motion and weight-bearing and an early return to sports (Shelbourne and Nitz 1992; Shelbourne et al. 1995). It is now customary to allow return to full sports activities six months after the procedure (MacDonald et al. 1995; Shelbourne and Nitz 1992), with some authors advocating a return to sports as early as four months post-operatively (De Carlo et al. 1999; Howell and Taylor 1996).

There are, however, several reasons for concern about the assumption that “aggressive” rehabilitation with a rapid return to sports is appropriate. Firstly, studies regarding how much loading and motion a knee with a healing ACL graft can sustain without permanently stretching the graft, disrupting the graft, or creating failure of graft fixation are still lacking (Beynnon et al. 2002). Secondly, despite “aggressive” rehabilitation, current protocols appear to be insufficient in order to restore muscle size and strength after reconstruction of the ACL, as described by a number of authors (Table 1).
Table 1. Summary of recent research measuring quadriceps muscle strength, thigh circumference, and thigh muscle cross-sectional area (CSA) after ACL reconstruction.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Patients</th>
<th>Time after surgery (months)</th>
<th>Muscle strength*</th>
<th>Thigh circumference*</th>
<th>Muscle CSA*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderson et al. 2002</td>
<td>45 (12 women and 33 men)</td>
<td>12</td>
<td>81</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Andrade et al. 2002</td>
<td>14 men</td>
<td>8</td>
<td>67</td>
<td>98</td>
<td>Not measured</td>
</tr>
<tr>
<td>Arangio et al. 1997</td>
<td>33 (9 women and 24 men)</td>
<td>49±7</td>
<td>90</td>
<td>98</td>
<td>91</td>
</tr>
<tr>
<td>Carter and Edinger 1999</td>
<td>106</td>
<td>6</td>
<td>68 (PT), 74 (ST), 78 (ST/G)</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Järvelä et al. 2002</td>
<td>86 (21 women and 65 men)</td>
<td>84±1</td>
<td>90</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Keys et al. 2001</td>
<td>31 (9 women and 22 men)</td>
<td>6</td>
<td>93</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Mattacola et al. 2002</td>
<td>20 (9 women and 11 men)</td>
<td>18±10</td>
<td>84</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>McHugh et al. 1998</td>
<td>102 (46 women and 56 men)</td>
<td>6</td>
<td>67</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Petschnig et al. 1998</td>
<td>25 men</td>
<td>12</td>
<td>87</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Pfeifer and Banzer 1999</td>
<td>39 (17 women and 22 men)</td>
<td>14±2</td>
<td>78</td>
<td>97</td>
<td>Not measured</td>
</tr>
<tr>
<td>Risberg et al. 1999</td>
<td>60 (28 women and 32 men)</td>
<td>24</td>
<td>93</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Ross et al. 2002</td>
<td>50 (14 women and 36 men)</td>
<td>29±15</td>
<td>92</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Sekiya et al. 1998</td>
<td>107 (71 women and 36 men)</td>
<td>24 (range 12 to 60)</td>
<td>78</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Urabe et al. 2002</td>
<td>44 (20 women and 24 men)</td>
<td>12</td>
<td>78</td>
<td>98</td>
<td>Not measured</td>
</tr>
<tr>
<td>Wojtys and Huston 2000</td>
<td>25 (9 women and 16 men)</td>
<td>6/12/18</td>
<td>76/86/90</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Yoon and Hwang 2000</td>
<td>24 men</td>
<td>20±15</td>
<td>68</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
<tr>
<td>Østerås et al. 1998</td>
<td>90 women</td>
<td>6±2</td>
<td>71</td>
<td>Not measured</td>
<td>Not measured</td>
</tr>
</tbody>
</table>

PT = patellar tendon graft, ST = semitendinosus tendon graft, ST/G = semitendinosus and gracilis tendon graft
*Expressed as percent of the uninvolved leg
To make matters worse, it has been suggested that the deficits may even be an underestimation when the contralateral limb is used for comparison (Hiemstra et al. 2000).

With the exception of Pfeifer and Banzer (1999), no explanations as to why it was not possible to restore muscle size and strength after ACL reconstruction are offered by the authors mentioned in Table 1. Pfeifer and Banzer (1999) explained the pronounced strength deficits over a long time period after ACL reconstruction which were noted in their study as being due to insufficient rehabilitation schedules, rather than neuromuscular deficits, since only three from 39 patients showed force increases upon electrical stimulation above maximal voluntary force. The authors did not, however, discuss the way in which the rehabilitation programmes were insufficient. Nevertheless, there are at least three possible reasons why ACL rehabilitation protocols are insufficient when it comes to regaining muscle strength and volume (Augustsson 2002).

Firstly, it may be that current ACL protocols focus too heavily on functional sport-specific exercises and exercises related to loading situations in everyday life, possibly at the expense of weight training. Secondly, weight training intensity may be too low during ACL rehabilitation in order to increase strength and muscle volume. For instance, Risberg et al. (1999) used a rehabilitation programme in which patients performed three sets of 15 to 30 repetitions, which is mostly muscular endurance training. Not surprisingly, patients undergoing ACL reconstruction required two years or more to achieve normal quadriceps muscle performance using the protocol developed by Risberg et al. (1999). Rhea et al. (2003) carried out a meta-analysis of 140 studies to identify the dose-response relationship for strength training. It was concluded that training with a mean intensity of 60% of 1 RM elicited maximal gains in untrained individuals, whereas 80% was most effective in those who were trained. It is quite possible that, for various reasons (e.g. physiotherapists avoiding heavy weight training by way of precaution), ACL rehabilitation protocols generally never reach these levels of intensity. Thirdly, it has been shown that compliance with the programme decreases with time during ACL rehabilitation (Beynnon et al. 2002). This is unfortunate, as a considerable length of time often is necessary to achieve training-induced hypertrophy. Indeed, increased strength performance as a result of weight training lasting less than 20 weeks has been associated primarily with neural adaptation rather than hypertrophy (Sale 1988). It is therefore possible that the time patients spend on weight training is not sufficient to induce hypertrophy during ACL rehabilitation.

Collectively, these studies indicate that current weight training protocols during ACL rehabilitation may be insufficient in terms of strength and muscle volume acquisition, which probably increases the risk of overuse injury or re-injury when individuals return to physically demanding work or sports. Further, programmes and techniques used by athletes such as body builders and power
lifters are, arguably, far more advanced compared with weight training performed in the clinical setting (Augustsson et al. 2003). ACL rehabilitation protocols should therefore be further developed to optimise the exercises used for the training of muscle volume and strength. Scientific studies of weight training principles and methods used by athletes’ should form the basis of rehabilitation exercise protocols.

**Biomechanical studies of ACL grafts**

Traditional rehabilitation programmes have been based on animal studies that found that graft maturity is not achieved until about one year after surgery, as the graft goes through a stage of early necrosis (DeMaio et al. 1992). Some authors recommend jogging at four months and sports at six to nine months when it is thought the graft has undergone sufficient maturation (DeMaio et al. 1992; Noyes and Barber-Westin 1997; Podesta et al. 1990). These recommendations are based on animal studies. Clancy et al. (1981) found that, in monkeys, patellar tendon reconstruction had 80% of its original strength at one year. Yoshiya et al. (1987) showed in dogs that ultimate graft failure was only 30% of control at 20 months. Other animal studies have shown that, at three to four months, graft peak ultimate load is 20% to 45% of the normal ACL, and, at 12 to 24 months, the peak load was 33% of the normal ACL (DeMaio et al. 1992).

Other studies, however, suggest that the graft never loses its viability nor significant strength (Kleiner et al. 1986; Rougraff et al. 1993). Kleiner et al. (1986) demonstrated that, at three weeks after implantation, fibroblasts that repopulated the graft had a high synthetic capability. Rougraff et al. (1993) biopsied human autogenous patellar tendon grafts and found viability as early as three weeks postoperatively with no stage of complete necrosis. Amiel et al. (1983) have shown that the patellar tendon graft is immediately able to respond to the environment. Hannafin et al. (1995) supported these results when they demonstrated that stress had a positive influence on healing, collagen formation, and alignment along the lines of stress for greater strength. Moreover, in a 37-year-old man eight months after autogenous patellar graft, Beynnon et al. (1997b) found that the reconstructed tendon exhibited biomechanical behaviour superior to that found in animal studies with an ultimate failure equal to 87% of the normal ACL.

Taken together, the limits of strain that are safe for a healing ACL graft are not clear, and the exercises that are either safe or harmful during rehabilitation have currently not been identified (Beynnon et al. 2002). So, the application of findings from biomechanical studies of healing ACL grafts to the clinical environment and the rehabilitation of a healing graft must be performed with caution.
Summary of problem areas presented in the introduction

In the introduction, the objective was to discuss the often complex relationships between various factors and to focus on some problem areas when it comes to athletic and therapeutic training and testing.

- Current rehabilitation programmes appear to be insufficient when it comes to restoring muscle size and strength after ACL reconstruction, as leg strength deficits often exist one year or more after surgery (Anderson et al. 2002; Arangio et al. 1997; Risberg et al. 1999; Witvrouw et al. 2001). As it is now customary to permit patients to return to recreational and competitive sports six months after surgery, more attention needs to be paid to rehabilitation protocols. Few studies have, however, investigated the effect of various weight training regimens (closed and open kinetic chain exercises, for example) on strength and functional performance improvements and whether these training forms are similarly effective, or whether they complement each other, in producing strength and functional performance gains. This topic is addressed in Studies I and III.

- Although closed and open kinetic chain strength tests are frequently used to monitor the effects of rehabilitation, the ability of these tests to relate to functional performance is not clear. Moreover, studies investigating whether closed and open kinetic chain strength tests can be used interchangeably, or whether they complement each other, to reflect functional performance, are lacking in current literature. This topic is addressed in Study II.

- Injuries often tend to occur at the end of a sporting event, when a participant is fatigued (Dugan and Frontera 2000; Feagin et al. 1987; Östenberg and Roos 2000). It has been our observation, however, that current clinical tests of functional performance are typically performed under non-fatigued conditions. This may constitute a problem when deciding whether an individual is fully rehabilitated and fit for full sports participation. A more realistic approach, that has yet to receive scientific attention, might be to perform functional tests under conditions of fatigue. This topic is addressed in Studies IV and V.
**Aims of the investigation**

**Study I**
To compare the effect of closed versus open kinetic chain weight training of the thigh muscles.

**Study II**
To compare the ability of closed and open kinetic chain tests of muscular strength to assess functional performance.

**Study III**
To investigate the effect of “pre-exhaustion” exercise on lower-extremity muscle activation during a leg press exercise.

**Study IV**
To evaluate single-leg hop performance following “pre-exhaustion” exercise in a test-retest design. Further, to investigate how fatigue influences lower-extremity joint kinematics and kinetics during single-leg hops.

**Study V**
To investigate the ability of a new hop test, performed under conditions of fatigue, to determine functional deficits in patients after anterior cruciate ligament reconstruction.
Subjects

Study I
Sixteen male and eight female subjects, healthy and generally physically active with asymptomatic back, hip and knee function, volunteered to participate in the study. The subjects were randomised into a closed and an open kinetic chain group. Due to illness and time constraints three subjects (one male in each group and one female in the open kinetic chain group) failed to complete the study. The closed kinetic chain group consisted of seven male and four female subjects. Their mean (±SD) age, body mass and height were 25±6 years, 66±11 kg and 177±11 cm respectively. The open kinetic chain group consisted of seven male and three female subjects. Their mean (±SD) age, body mass and height were 26±5 years, 73±12 kg and 181±10 cm respectively.

Study II
Sixteen male subjects, healthy and generally physically active with asymptomatic back, hip and knee function, volunteered to participate in the study. Their mean (±SD) age, body mass and height were 27±5 years, 78±9 kg and 183±9 cm respectively.

Study III
Seventeen healthy male subjects, with a mean (±SD) age, body mass and height of 26±4 years, 77±6 kg and 182±6 cm respectively, volunteered to participate in the study. All the subjects were recreational weight trainers with an average (±SD) of 5.5±4 years resistance training experience.

Study IV
Eleven male subjects, healthy and generally physically active with asymptomatic back, hip and knee function, volunteered to participate in the first experiment. Their mean (±SD) age, body mass and height were 27±5 years, 75±10 kg and 182±4 cm respectively. Eight healthy and generally physically active male subjects volunteered to participate in the second experiment. Their mean (±SD) age, body mass and height were 31±6 years, 80±6 kg and 185±4 cm respectively.

Study V
Nineteen male patients with a unilateral ACL injury who had undergone ACL reconstruction were recruited for this study in a consecutive manner from a cohort of patients that had undergone reconstruction of the ACL at Sahlgrenska University Hospital, Östra (Figure 5).
The descriptive data for the patients \((n=19)\) in Study V were mean (±SD) age, body mass and height of 28±5 years, 79±8 kg and 182±5 cm respectively. The mean (±SD) time since surgery was 11±2 months, whereas the mean time (±SD) between the index injury and reconstruction was 22±17 months.

**Figure 5.** Description of the patients included in Study V.
Ethics

All the studies were approved by the Ethics Committee at Göteborg University.
Methods

Weight training
In Study I, subjects performed maximal, progressive weight training, twice a week on non-consecutive days, for six weeks (Table 2).

The closed kinetic chain group performed a barbell squat programme, mainly activating the quadriceps and adductor muscles of the thigh (Tesch 1993). The open kinetic chain group performed a weight machine knee-extension and hip-adduction programme, activating the quadriceps and adductor muscles of the thigh separately (Figure 6).

TABLE 2. Weight training programmes.

<table>
<thead>
<tr>
<th>Closed kinetic chain group*</th>
<th>Open kinetic chain group§</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barbell squat</td>
<td>Weight machine knee-extension</td>
</tr>
<tr>
<td></td>
<td>Weight machine hip-adduction</td>
</tr>
</tbody>
</table>

Subjects performed four sets of each exercise at 10 RM
*Two minutes' rest allowed between sets
§One minute's rest allowed between sets

Figure 6. The closed kinetic chain group performed a barbell squat programme (left picture). The open kinetic chain group performed a weight machine knee-extension (right picture) and hip-adduction programme. Photos by Roland Thomeé and Jesper Augustsson.
Strength testing
An isokinetic knee-extension test (Figure 7) and a 3 RM barbell squat test were used to evaluate the training-induced effects on strength (Study I) and to compare the ability of closed and open kinetic chain tests of muscular strength to assess functional performance (Study II).

The isokinetic knee-extension test was performed using a Kinetic Communicator II dynamometer (Kin-Com, Chattecx Corp., Chattanooga, USA).

In Study III, each subject’s 10 RM was determined for a leg press exercise (Figure 7) and a knee-extension exercise by using the maximum weight that could be lifted for 10 consecutive repetitions. The weight lifted for each trial was increased by 5-10 kg until failure occurred.

In Studies IV and V, each subject’s unilateral 1 RM for the right and the left leg was determined for a knee-extension exercise by using the maximum weight that could be lifted for one repetition.

Functional performance testing
In Studies I and II, a vertical jump test was performed with the subject standing erect on a platform, quickly performing a countermovement and jumping for maximal height.

In Studies IV and V, functional performance was assessed by a single-leg hop test for distance in which the subject was instructed to stand on one leg and to position his toes to a mark on the floor. The subject was then instructed to hop forward as far as possible and to land on the same leg. The subject was allowed to swing his arms freely as he jumped in Study IV, but in Study V, the patient was instructed to hold his hands on his hips throughout the jump.

All the strength and functional tests in Study V were conducted in a blinded

Figure 7. In Studies I and II, an isokinetic knee extension test was performed using a Kin-Com dynamometer (left picture). In Study III, each subject’s 10 RM was determined for a leg press exercise (right picture) and a knee extension exercise. Photos by Jesper Augustsson.
fashion, as patients concealed their knees by wearing elastic wraps. In this way, the test leader (J.A.) did not know whether the involved or the non-involved leg was being tested during a particular test session.

Electromyography (EMG)
In Study III, EMG was used to investigate the effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise. Bipolar surface electrodes with a diameter of 9 mm (Red Dot, 3M Medica, Borken, Germany) were placed over the bellies of the rectus femoris, vastus lateralis, and gluteus maximus muscles using a standardised method described by Isear et al. (1997).

A Tubigrip (Seaton Healthcare Group, Oldham, England) compression wrap was applied to the test extremity (right leg) to maintain electrode placement. Heavy adhesive tape was used to secure electrode placement on the gluteus maximus muscle. All the test sites were identified and prepared by the same investigator.

The maximal voluntary isometric activation (MVIA) procedure
EMG was recorded during MVIA for each muscle and was used as a reference value for comparison of muscle activity with and without pre-exhaustion exercise during the leg press exercise. Three MVIA s were performed against a fixed resistance for each muscle. Each EMG sample included the entire MVIA interval of four seconds’ duration. The largest RMS value of the three MVIA s was designated the reference EMG and was used for normalisation.

The pre-exhaustion exercise procedure
Subjects were placed in the knee-extension and leg press station (Figure 8). Subjects performed one set of pre-exhaustion exercise of the quadriceps muscles to the point of fatigue using the knee-extension exercise at a load of 10 RM. Immediately after that exercise, EMG was recorded from the rectus femoris, vastus lateralis and gluteus maximus muscles simultaneously during one set of the leg press exercise performed at a load of 10 RM. After a 20-minute rest period, EMG was recorded as subjects once again performed one set of the leg press exercise (without pre-exhaustion exercise) at a load of 10 RM. Subjects terminated the exercise sets on the completion of 10 RM or muscle failure.
Figure 8. Testing setup: in Study III, subjects performed a knee extension exercise (pre-exhaustion), immediately followed by a leg press exercise. Both exercises were performed at a 10 RM load.
Hop testing under fatigued conditions
In Studies IV and V, hop performance was compared in two standardised test conditions—non-fatigued and immediately following pre-exhaustion exercise of the quadriceps muscle at different percentages of 1 RM strength (Figure 9).

Biomechanical analysis
For the second experiment in Study IV, a biomechanical analysis of maximal single-leg hops during fatigued and non-fatigued conditions, the same test protocol was used as for the first experiment.

Figure 9. Testing set-up: in Study V, the patients performed unilateral pre-exhaustion exercise of the quadriceps muscle until failure using a variable resistance knee-extension machine at a load of 50% of 1 RM, followed by a single-leg hop.
Statistical methods

Study I
Student’s $t$-test for independent groups was used to compare the difference in scores between groups, while a paired $t$-test was used for pre-post comparisons within groups. Means and standard deviations were calculated for all variables, except physical activity (ordinal) where median and interquartile range were computed. Additionally, the Mann-Whitney $U$ test was used to compare the physical activity level of subject groups.

Study II
To examine the relationship between the values of the closed and open kinetic chain tests of muscular strength with the test of functional performance, Pearson product-moment correlation coefficients were determined. Relationship differences between the closed and open kinetic chain tests of muscular strength variables were then computed using a two-tailed $t$-test for testing differences between two dependent correlation coefficients (Guilford and Fruchter 1973).

Study III
Muscle activation amplitude obtained during the pre-exhaustion exercise procedure was normalised relative to the MVIA (test electromyograph amplitude/electromyograph amplitude of MVIA multiplied by 100). A paired-samples $t$-test was used to compare the average RMS values collected during the leg press exercise with and without pre-exhaustion exercise. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was compared using a paired-samples $t$-test.

Study IV
For the first experiment, the intraclass correlation (ICC) coefficient was computed for the analysis of test-retest reliability under different hop test conditions, according to Shrout and Fleiss (1979). The Friedman test was used to determine differences in hop performance between fatigued and non-fatigued hop test conditions. Differences between the number of hop trials and knee-extension repetitions performed at test and retest were computed using the Wilcoxon signed-rank test. For the second experiment, comparisons between the biomechanical variables that were obtained were made with the Friedman test.
Study V
Based on a hypothesised 5-10% difference in performance between hop-test conditions using the involved and non-involved leg, the number of patients required to achieve a power of 0.90 was estimated by power analysis.

The intraclass correlation (ICC) coefficient was computed for analyses of the test-retest reliability of the 1 RM test, according to Shrout and Fleiss (1979). Differences in performance between fatigued and non-fatigued hop-test conditions for the involved and the non-involved side, and differences between the number of hop trials and knee-extension repetitions, were analysed using paired $t$-tests.

The significance was considered at the $\alpha$ level of $P<0.05$ in all studies.
Summary of the papers

**Study I:** Weight training of the thigh muscles using closed vs. open kinetic chain exercises: a comparison of performance enhancement.

*Introduction:* Resistance training is commonly used in sports, for prevention of injuries and in rehabilitation. The purpose of this study was to compare closed versus open kinetic chain weight training of the thigh muscles and to determine which mode resulted in the greatest performance enhancement.

*Methods:* Twenty-four healthy subjects were randomised into a barbell squat or a knee-extension and hip-adduction variable resistance weight machine group and performed maximal, progressive weight training twice a week for six weeks. All the subjects were tested prior to training and at the completion of the training period. A barbell squat 3 RM, an isokinetic knee-extension, and a vertical jump test were used to monitor the effects of training.

*Results:* Significant improvements were seen in both groups in the barbell squat 3 RM test. The closed kinetic chain group improved by 23 kg (31%), which was significantly more than the 12 kg (13%) seen in the open kinetic chain group. In the vertical jump test, the closed kinetic chain group improved significantly, five cm (10%), while no significant changes were seen in the open kinetic chain group (test of differences across groups was not significant). A large increase in training load was observed in both subject groups; however, improvements in isotonic strength did not transfer to the isokinetic knee-extension test.

*Conclusion:* The results may be explained by neural adaptation, weight training mode and specificity of tests.

**Study II:** Ability of closed and open kinetic chain tests of muscular strength to assess functional performance.

*Introduction:* The purpose of this study was to investigate the ability of closed and open kinetic chain tests of muscular strength to assess functional performance.

*Methods:* Sixteen healthy male subjects, with a mean (±SD) age, body mass and height of 27±5 years, 78±9 kg and 183±9 cm respectively, volunteered to participate in the study. In the closed kinetic chain test (involving muscles working across multiple joints), the subjects performed a 3 RM barbell squat. The open kinetic chain test (involving muscles working across a single joint) consisted of a concentric isokinetic knee-extension at an angular velocity of 60°/sec and was performed using a Kinetic Communicator II dynamometer. The test of
functional performance (vertical jump) was performed with the subject standing erect, quickly performing a counter-movement jump for maximal height.

**Results:** Moderately strong correlations between the test of functional performance and the closed and open kinetic chain tests of muscular strength were noted, $r=0.51$ and $r=0.57$, respectively ($P<0.05$). A correlation of $r=0.64$ was obtained between the closed and the open kinetic chain test of muscular strength ($P<0.01$) (Figure 10).

**Conclusion:** It is suggested that the effect of training or rehabilitation interventions should not be based exclusively on tests of muscular strength. Instead, various forms of dynamometry including functional performance tests could be recommended.

![Figure 10. The correlations between the test of functional performance and the closed and open kinetic chain tests of muscular strength. In parentheses the coefficient of determination ($r^2$) values are shown: open kinetic chain knee extension strength, for example, accounted for 32% of jumping performance.](image)
**Study III:** Effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise.

*Introduction:* The purpose of this study was to investigate the effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise. Pre-exhaustion exercise, a technique frequently used by weight trainers, involves combining a single joint exercise, followed immediately by a related multijoint exercise (e.g. a knee-extension exercise followed by a leg press exercise).

*Methods:* Seventeen healthy male subjects performed one set of a leg press exercise with and without pre-exhaustion exercise, which consisted of one set of a knee-extension exercise. Both exercises were performed at a load of 10 RM. EMG was recorded from the rectus femoris, vastus lateralis and gluteus maximus muscles simultaneously during the leg press exercise. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was also documented.

*Results:* The activation of the rectus femoris and the vastus lateralis muscles during the leg press exercise was significantly less when subjects were pre-exhausted ($P<0.05$). No significant EMG change was observed for the gluteus maximus muscle (Figure 11). When in a pre-exhausted state, subjects performed significantly ($P<0.001$) fewer repetitions of the leg press exercise.

*Conclusion:* Our findings do not support the popular belief of weight trainers that performing pre-exhaustion exercise is more effective in enhancing muscle activity compared with regular weight training. Conversely, pre-exhaustion exercise may have disadvantageous effects on performance, such as decreased muscle activity and a reduction in strength, during multijoint exercise.
Figure 11. Mean and SEM of EMG activity (expressed as percent of maximal voluntary isometric activation) during a leg press exercise with compared to without pre-exhaustion exercise for the rectus femoris, vastus lateralis, and gluteus maximus muscles, respectively. *Indicates difference (p=0.034) from pre-exhausted condition. **Indicates difference (p=0.001) from pre-exhausted condition.
**Study IV:** Development of a single-leg hop test performed under fatigued conditions using pre-exhaustion exercise: reliability and biomechanical analysis.

*Introduction:* A pre-exhaustion exercise protocol was combined with single-leg hop testing to improve the possibilities to evaluate the effects of training or rehabilitation interventions.

*Methods:* In the first test-retest experiment, 11 healthy male subjects performed two trials of single-leg hops under three different test conditions: non-fatigued and following pre-exhaustion exercise which consisted of unilateral weight machine knee-extensions until failure occurred at 80% and 50% respectively, of 1 RM strength. For the second experiment, eight healthy male subjects performed the pre-exhaustion exercise protocol to investigate how fatigue influences lower-extremity joint kinematics and kinetics during single-leg hops. Hip, knee and ankle joint angles, moments and powers, as well as ground-reaction forces were recorded with a six-camera, motion-capture system and a force platform. The recovery of hop performance following the fatiguing exercise was also measured.

*Results:* ICC coefficients ranged from 0.75 to 0.98 for different hop test conditions (measured as maximal hop length), indicating that all the tests were highly reliable. During the take-off for the single-leg hops, hip and knee flexion angles, generated powers for the knee and ankle joints, and ground-reaction forces decreased for the fatigued hop conditions compared with the non-fatigued condition (*P*<0.05) (Figure 12). Compared with landing during the non-fatigued condition, hip moments and ground-reaction forces were lower for the fatigued hop conditions (*P*<0.05). Absorbed power was two to three times greater for the knee than for the hip and five to ten times greater for the knee than for the ankle during landing for all test conditions (*P*<0.05). Most measured variables had recovered three minutes post-exercise.

*Conclusion:* It is concluded that the pre-exhaustion exercise protocol combined with single-leg hop testing was a reliable method for investigating functional performance under fatigued test conditions. Further, subjects utilised an adapted hop strategy which employed less hip and knee flexion and generated powers for the knee and ankle joints during take-off, as well as less hip joint moments during landing under fatigued conditions. The large negative power values observed at the knee joint during the landing phase of the single-leg hop, during which the quadriceps muscle activates eccentrically, indicate that not only hop distance but also the ability to perform successful landings should be investigated when assessing dynamic knee function.
Figure 12. Representative hip, knee and ankle joint angles, moments and powers, as well as ground-reaction forces during the take-off for a single subject for non-fatigued and fatigued (50% of quadriceps muscle 1 RM-strength) hop conditions. The vertical dotted lines indicate the time of take-off when the subject becomes airborne.
Study V: Ability of a new hop test to determine functional deficits after anterior cruciate ligament reconstruction.

Introduction: The aim of this study was to investigate the ability of a new hop test, performed under conditions of fatigue, to determine functional deficits after anterior cruciate ligament (ACL) reconstruction. The test consists of a pre-exhaustion exercise protocol combined with a single-leg hop.

Methods: Nineteen male patients with ACL reconstruction (mean time after operation 11 months) who exhibited normal single-leg hop symmetry values (≥90% compared with the non-involved extremity) were tested for 1 RM strength of a knee-extension exercise. The patients then performed single-leg hops following a standardised pre-exhaustion exercise protocol, which consisted of unilateral weight machine knee-extensions until failure at 50% of 1 RM.

Results: Although no patients displayed abnormal hop symmetry when non-fatigued, 68% of the patients showed abnormal hop symmetry for the fatigued test condition. Sixty-three per cent exhibited 1 RM strength scores of below 90% of the non-involved leg. Eighty-four per cent of the patients exhibited abnormal symmetry in at least one of the tests (Figure 13).

Figure 13. Results of the tests of functional ability and 1 RM knee-extension strength in Study V. Values shown are percentages of patients with ACL reconstruction within the normal range.
Conclusion: Our findings indicate that patients are not fully rehabilitated 11 months after ACL reconstruction. The pre-exhaustion exercise protocol combined with the single-leg hop test improved testing sensitivity when evaluating lower-extremity function after ACL reconstruction. For a more comprehensive evaluation of lower-extremity function after ACL reconstruction, it is therefore suggested that functional testing should be performed both under non-fatigued and fatigued test conditions.
Discussion

**Kinetic chain weight training and strength assessment (Studies I, II and III)**

In Study I, six weeks of closed kinetic chain weight training resulted in larger improvements in a 3 RM barbell squat test than did open kinetic chain weight training. Although the closed kinetic chain group improved their jumping ability, there was no difference across groups. No changes were seen in subject groups in the isokinetic knee-extension test. The results may be explained by neural adaptation, weight training mode and specificity of tests.

In Study I, the increase in training load (50% and 100% respectively for the closed and the open kinetic chain group) during six weeks of weight training was different and it could be theorised that single joint weight machine exercise produces greater gains in training load in short-term weight training programmes compared with multijoint free weight exercise. This is in accordance with Chilibeck et al. (1998) who performed a resistance training study in which prolonged neural adaptation using multijoint exercise was noted, which may have delayed hypertrophy. One reason for this may be that, initially, high-intensity training may be difficult due to high demands relating to co-ordination and technique. Conversely, with less complex single joint exercise, early gains in strength were accompanied by muscle hypertrophy and, presumably, faster neural adaptation (Chilibeck et al. 1998). Moreover, McBride et al. (2003) reported that 12 weeks of single joint weight training promoted significantly greater percentage strength gains compared with multijoint weight training. Taken together, it appears that neural adaptation and, as a result, hypertrophy, may occur earlier with single joint exercises than with multijoint exercises. It therefore appears as if the time course for the adaptation of the muscular system is different depending on whether multijoint or single joint resistance exercise is used (Figure 14).

It is generally believed that high forces which activate both high- and low-threshold motor units are essential for muscle growth to occur during weight training (Kraemer et al. 1998). Accordingly, in Study I, subject groups performed high-intensity weight training (exercise sets were performed at a load of 10 RM, which approximates 80% of 1 RM). However, Takarada et al. (2000a) reported increases in muscle strength and cross-sectional area in a group of novice, older women after low-intensity resistance training (50% of 1 RM), combined with vascular occlusion. The improvements in muscle strength and cross-sectional area were greater than in a group that performed low-intensity resistance training alone and comparable to a group that followed a high-intensity resistance training protocol (80% of 1 RM). Another study by Takarada
et al. (2002b) reported that, in highly trained athletes, low-intensity resistance exercise caused an increase in muscle size, strength and endurance, when combined with vascular occlusion. Moreover, two studies have shown promising results for the vascular occlusion technique after reconstruction of the ACL (Ohta et al., 2003; Takarada et al., 2000b). Takarada et al. (2000b) reported that vascular occlusion, without being combined with any exercise, diminished the post-operation disuse hypertrophy of knee extensors in patients who underwent ACL reconstruction. Ohta et al. (2003) compared the effects of low-load resistance training with moderate restriction of blood flow with traditional postoperative rehabilitation after reconstruction of the ACL. A significant increase in leg strength and thigh muscle cross-sectional area was noted in the experiment group as compared with the control group.

Taken together, it appears that high-intensity weight training, such as the protocol used in Study I, may not be necessary if the goal is to obtain increases in strength and muscle volume. In fact, low-intensity training combined with vascular occlusion may augment strength and muscle size normally only associated with high-intensity training (Takarada et al., 2000a). It is important to realise, however, that traditional high-intensity training has more potential for strengthening the passive structures of muscle-tendon units and ligaments, for example. This is a valuable aspect of weight training when it comes to assisting in the prevention of and rehabilitation from injury. Patients are, however, often

Figure 14. Diagram showing the possible time course for the adaptation of the muscular system depending on whether multijoint or single joint weight training is performed.
not able to advance to high-intensity weight training, even after extensive periods of rehabilitation (due to pain, for example) and, as a result, they frequently suffer from muscular hypertrophy. One possible solution to this dilemma could be for the patient to perform low-intensity weight training, combined with vascular occlusion. We are currently performing research in this area at our laboratory.

In Study II, we investigated the ability of closed and open kinetic chain tests of muscular strength to assess functional performance. Moderately strong correlations were noted between the test of functional performance and the closed and open kinetic chain tests of muscular strength, \( r = 0.51 \) and \( r = 0.57 \) respectively \((P<0.05)\). A correlation of \( r = 0.64 \) was obtained between the closed and the open kinetic chain test of muscular strength \((P<0.01)\). This correlation \((r=0.64)\) indicates that closed and open kinetic chain tests of strength complement each other in their ability to assess functional performance.

In Study III, we showed that pre-exhaustion exercise had exactly the opposite effect on muscle activation to that suggested by weight trainers using this technique. In our study, pre-exhaustion exercise (a single joint knee-extension exercise) resulted in a reduction rather than an increase in the activation of the quadriceps muscle during a multijoint leg press exercise. Subjects also performed fewer repetitions of the leg press exercise when in a pre-exhausted state. It thus appears that the pre-exhaustion technique may not enhance muscle volume and strength more effectively, compared with regular weight training, as suggested by weight trainers using this technique (Kamali 2001). The negative result of Study III was unfortunate, because there is a need for effective methods of restoring quadriceps muscle strength and size after ACL reconstruction, for example.

Although advocates of pre-exhaustion exercise have proposed this technique in order to stimulate more muscle growth (Darden 1983), Study III is to our knowledge the first study of the effect of pre-exhaustion exercise on muscle activation and performance. Studies of the effect of exercise order during a particular weight training session (that is, multijoint exercises, such as squats, being placed at the end of the workout compared with multijoint exercises being placed at the beginning of the workout), have, however, previously been performed. Sforzo and Touey (1996) investigated the significance of performing multijoint exercises during the first part of a workout and vice versa. It was determined that when multijoint exercises were preceded by single joint exercises, the total training volume was significantly lower compared with when multijoint exercises were followed by single joint exercises. The findings noted by Sforzo and Touey (1996) thus support the results of Study III, which indicate that performing single joint exercises first, followed by multijoint exercise, appears to be less effective in producing strength and muscle size gains. To date, however, no training studies have been performed on the effects of pre-
exhaustion exercise. As a result, the possibility that pre-exhaustion exercise could result in greater gains in muscle strength or hypertrophy than regular weight training during long-term weight training cannot be ruled out.

**Functional performance testing (Studies IV and V)**
The aim of Study IV was firstly to develop and to examine the reliability of a single-leg hop test performed under standardised, fatigued conditions using pre-exhaustion exercise and, secondly, to obtain biomechanical information about the effect of quadriceps muscle fatigue on the kinetic and kinematic behaviour of the lower-extremities during single-leg hops. For the first experiment, the test-retest reliability of different hop-test conditions was determined. Hop performance under all three test conditions was found to have high test-retest reliability. We have thus developed a reliable method that is easy to perform and record and which, in the clinical setting, can be used to compare functional performance under different, standardised test conditions.

As for the biomechanical part of Study IV, during the take-off for the single-leg hops, the main findings were that hip and knee flexion angles, generated powers for the knee and ankle joints and ground-reaction forces decreased for the fatigued hop conditions compared with the non-fatigued condition. Compared with landing during the non-fatigued condition, hip moments and ground-reaction forces were lower for the fatigued hop conditions. The impact during landing resulted in powers during single-leg landing tasks that were two to three times greater for the knee than for the hip and five to ten times greater for the knee than for the ankle, for all test conditions. In simpler terms: by “putting the brakes on” during the single-leg landings, the muscles acting across the knee had to “brake” two to three times harder than the muscles acting across the hip and five to ten times harder than the muscles acting across the ankle.

Based on the results of Study IV, it is possible that the focus of interest should shift from the ability to generate power during the take-off to the ability to absorb power during landing, during single-leg testing for clinical or scientific purposes. We therefore suggest that, in order to obtain a more comprehensive assessment of knee function (after ACL injury or reconstruction, for example), attention should not centre exclusively on comparisons between the hop distance on the injured and uninjured sides but also on the ability successfully to perform landings. Our findings are in accordance with the results of other studies (Ernst et al. 2000; Juris et al. 1997; Webster et al. 2003) in which landing forces during different jumps and hops were investigated in patients after ACL reconstruction. Ernst et al. (2000) suggested that landing forces may be inadequately attenuated following ACL reconstruction, which could expose the joint structures to injury. Juris et al. (1997) tested the ability of patients after ACL reconstruction to both
produce force (maximal hop for distance) and absorb force (controlled hop, with the requirement of keeping the foot fixed at the landing position until stable). LSI scores revealed a greater deficit for force absorption than for force production. The authors speculated that force absorption is a more appropriate measure of functional capacity than force production. Finally, Webster et al. (2003) observed differences in landing strategies after hamstring and patellar tendon ACL reconstruction during the single-leg landing tasks. Interestingly, patients with patellar tendon grafts demonstrated reduced knee flexion angles and moments in the operated limb, whereas there were no differences between limbs for patients with hamstring grafts.

To summarise, many functional tests that are used for patients after ACL reconstruction measure the ability to generate force rather than the ability to attenuate it. In simpler terms: during different functional tests, such as single-leg hops, physiotherapists normally evaluate the ability of the muscles to function as “accelerators” (during the take-off) rather than “brakes” (during landing). Collectively, Study IV and other recent studies (Ernst et al. 2000; Juris et al. 1997; Webster et al. 2003) indicate that the ability to attenuate force (that is, the ability of the muscles to work as “brakes”) after ACL reconstruction may be an equally important functional outcome, particularly in relation to injury prevention.

In Study V, we developed a new test in which hop performance was investigated during conditions of fatigue in patients who had undergone ACL reconstruction. We hypothesised that this method would improve the possibility to evaluate the effects of rehabilitation interventions. We found that patients with normal single-leg hop ability achieved poorer results using the involved leg when performing single-leg hops in a fatigued state. The functional disability after ACL reconstruction could therefore be better delineated by the combination of pre-exhaustion exercise followed by a single-leg hop test, rather than a single-leg hop test alone. The higher sensitivity of the combined pre-exhaustion exercise protocol and single-leg hop test may be explained by its more demanding and thereby more discriminating nature compared with non-fatigued hop testing.

One possible reason for patients performing significantly worse using the involved leg during fatigued single-leg hop testing is that the knee joint provides the major energy absorption function during the landing phase of the single-leg hop (as noted in Study IV). The task of landing during the fatigued hop condition, using the involved leg, therefore presumably lead to great difficulties, at both a central and a peripheral level, for patients with ACL reconstruction.
Limitations
In Study I, a comprehensive evaluation of the effects of training is limited by the moderate number of subjects and by the moderate length of the weight training period. The sample size in Study II was moderate, but for our purposes we believed it was adequate. No definitive answers, however, regarding the exact correlation between tests of muscular strength and functional performance could be obtained from Study II. In Study III, we investigated the acute effects of pre-exhaustion exercise on muscle activation during a leg press exercise. It is possible that a long-term weight training study of the effect of pre-exhaustion exercise may have produced another outcome. In Study IV, the number of subjects was moderate and caution should therefore be exercised when generalising this data to apply to the general population. However, we believe the conclusions drawn in this study are on a par with the number of subjects. In Study V, the number of patients was moderate; however, sample size was determined using a power analysis.
Conclusions

• Six weeks of closed kinetic chain weight training resulted in larger improvements in a 3 RM barbell squat test than did open kinetic chain weight training. No significant changes were seen in subject groups in the isokinetic knee-extension test. The results may be explained by neural adaptation, weight training mode and specificity of tests.

• The moderate correlations between tests of muscular strength and the vertical jump test indicate that the results of strength measurements cannot fully assess functional performance. Consequently, it is suggested that the effect of training or rehabilitation interventions should not be based exclusively on tests of muscular strength. Instead, various forms of dynamometry including functional performance tests could be recommended.

• Despite the widespread use of pre-exhaustion exercise by weight trainers as a technique to increase the activation of the targeted (fatigued) muscle during multijoint exercise, pre-exhaustion exercise may have disadvantageous effects on muscle performance, such as reduced activation of the fatigued muscle. Moreover, subjects performed fewer repetitions of the leg press exercise when in a pre-exhausted state. Our data therefore indicate that weight trainers using this method should reconsider its effectiveness when it comes to producing strength and muscle size gains.

• The pre-exhaustion exercise protocol combined with single-leg hop testing may improve the possibilities to evaluate the effects of training or rehabilitation interventions, as it permits the examination of lower-extremity muscle function under conditions of fatigue. The large negative power values observed at the knee joint during the landing phase of the single-leg hop, during which the quadriceps muscle activates eccentrically, indicate that not only hop distance but also the ability to perform successful landings should be investigated when assessing dynamic knee function.

• The pre-exhaustion exercise protocol combined with the single-leg hop test improved testing sensitivity when evaluating lower-extremity function after ACL reconstruction. For a more comprehensive evaluation of lower-extremity function after ACL reconstruction, it is therefore suggested that functional testing should be performed under both non-fatigued and fatigued test conditions.
In summary
From the studies in this thesis, it is concluded that both closed and open kinetic chain training and testing of the lower-extremity can be recommended for sports and rehabilitation purposes. For a more realistic approach, when it comes to the functional performance testing of patients after ACL reconstruction, it is suggested that these tests should be performed both under non-fatigued and fatigued test conditions.
Clinical relevance

Despite being a difficult and complex task, maximal restoration of lower-extremity muscle function and functional performance, and thereby protection of the reconstructed ligament, should be a goal for the clinician and the patient after ACL reconstruction. In Study V, 68% of the patients displayed abnormal single-leg hop symmetry for the fatigued test condition, whereas 63% exhibited reduced quadriceps strength, 11 months after surgery. With these muscle function deficits in mind, several clinical questions need to be addressed, including the return to strenuous activities and sports participation. Many rehabilitation programmes suggest running, jumping, and twisting activities, as early as six months after the reconstruction. At this time, it is not possible to say how effective the knee muscles can be in attenuating impact forces and protecting ligaments after ACL reconstruction, if muscle performance is reduced to 70%, for example. As a result, there is clearly a need for more effective strengthening programmes for the lower-extremity muscles during rehabilitation after ACL reconstruction. Some of the most important variables in a programme of this kind include: 1) progression in the weight training protocol used; 2) the performance of both closed and open kinetic chain exercises; 3) the sequencing of the exercises to optimise the quality of the exercise intensity (multijoint exercises before single joint exercises) and 4) training intensity corresponding to at least 8–12 RM.
The future

Several questions have arisen during the study process and should lead to future studies.

- On the study of weight training: what is the optimal frequency, exercise intensity and training volume for optimal strength and muscle gains?
- On the study of strength assessment: what is the correlation between different tests of strength and power and athletic performance and to what extent are these tests sensitive to the effects of training?
- What is the effect of a reversed pre-exhaustion strategy, i.e. pre-exhausting small synergistic muscles rather than prime mover agonistic muscles?
- In what way are the kinetics and kinematics during functional tests, other than single-leg hops, influenced by muscle fatigue?
- If functional exercises are performed late in the training sessions (that is, in a fatigued state) during rehabilitation, is it possible to improve the ability to develop maximal power (single-leg hop or vertical jump ability, for example) in a fatigued state after ACL reconstruction?
Syftet med dessa studier var att få ökad kunskap när det gäller fysisk prestation förmåga hos friska personer och hos patienter med en opererad ligamentskada i knäleden. Vi redovisar resultat som handlar om träning i så kallad sluten och öppen rörelsekedja, vilka effekter man får av styrketräning och hur man på olika sätt kan mäta muskelstyrka. Dessutom har vi utvecklat ett nytt funktionellt test som utförs när en person är uttröttad.

I Studie I tittade vi på effekten av styrketräning i sluten rörelsekedja jämfört med öppen rörelsekedja på muskelstyrka och funktionell prestation förmåga. Sammanfattningsvis visade vår studie att sex veckors styrketräning enligt sluten rörelsekedja resulterade i större förbättringar av benstyrka jämfört med träning i öppen rörelsekedja.

I Studie II testade vi hur väl ett test av muskelstyrka enligt sluten respektive öppen rörelsekedja kunde bedöma funktionell prestation förmåga (i form av ett hopptest). Resultatet visade ett ganska starkt samband mellan hoppförmåga och de två testen av muskelstyrka. Vi tycker därför att mätning skall utföras av muskelstyrka i såväl sluten som öppen rörelsekedja och med test av funktionell prestation förmåga när effekten av träning eller rehabilitering ska bedömas.

I Studie III undersökte vi effekten av att kombinera styrketräning i sluten och öppen rörelsekedja genom så kallad "förutröttnings". Erfarna styrketränare anser att förutröttnings vid styrketräning gör att musklerna arbetar i högre grad jämfört med när muskeln inte är förutröttad. Aktiviteten i musklerna var dock mindre vid förutröttnings. Resultat av studien gör att vi ifrågasätter teorin att förutröttnings ger ett bättre träningsresultat vid styrketräning.

I Studie IV kombinerades förutröttningsmetoden som vi undersökte i Studie III med ett enbenshop för att försöka förbättra möjligheterna att utvärdera effekterna vid träning och rehabilitering. Vi såg att mätfelet var lågt när 11 friska deltagare utförde hoppen dels i utvilat och dels i uttröttat tillstånd. Dessutom undersökte vi på vilket sätt uttröttnings av lärmuskulaturen påverkade ledrörelser och krafter i höft-, knä- och fotled. Den bromsande kraften vid landning var två till tre gånger större för knäleden jämfört med höftleden och fem till tio gånger större jämfört med fotleden, både när deltagarna var utvilade och uttröttade.

I Studie V undersökte vi förmågan hos ett nytt hopptest, som gjordes under uttröttade förhållanden, att upptäcka brister hos patienter med en opererad ligamentskada i knäleden. Fastän att alla patienterna hade bra hoppförmåga med sitt opererade ben när de var utvilade, så hade två tredjedelar dålig hoppförmåga när de var uttröttade. Alltså gav uttröttningen, kombinerat med ett enbenshop,
ett bättre svar på hur duktiga patienterna egentligen var att hoppa med sitt ben efter operationen.

Sammanfattningsvis kan man säga att fastän mätningar av muskelstyrka är viktiga för att se effekten vid träning och rehabilitering, så kunde styrkemätningar inte fullt ut bedöma en persons funktionella prestationsförmåga. Brister i hoppförmåga efter en opererad ligamentskada i knäleden blev mer uppenbara när hopptestet utfördes när patienten var uttröttad. För att på ett bättre sätt upptäcka brister i förmåga efter en opererad ligamentskada föreslår vi därför att hopptest ska göras dels när patienten är utvilad och dels när patienten är uttröttad.
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References


Study I
Weight Training of the Thigh Muscles Using Closed Vs. Open Kinetic Chain Exercises: A Comparison of Performance Enhancement

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Most athletes use resistance training involving both free weights and weight machines to improve strength and power. The pros and cons of training with free weights vs. weight machines are widely discussed both among athletes and coaches, among physical therapists, as well as in sports science. Differences of opinion exist as to which method would result in optimal performance gains. Proponents of free weights emphasize functionality and a direct application to sporting activities (17). Conversely, the advocates of weight machines stress safety and less requirements of coordination compared with free weight training (16). There is a similar debate concerning the use of closed vs. open kinetic chain lower limb exercises during rehabilitation of operatively and conservatively managed injuries. A number of studies has compared the effect of closed vs. open kinetic chain lower limb exercises on knee ligament strain (7,11, 13,14,29), anterior-posterior tibiofemoral translation (17), and patellofemoral compression forces (9). The importance of using closed kinetic chain rehabilitation (5,20) and evaluation (10,27) has been stressed. However, few studies have investigated whether the effect of closed vs. open kinetic chain weight training on strength and performance is different.

When comparing free weights vs. weight machines or closed vs. open kinetic chain weight training, a dilemma exists in creating matching training conditions, e.g., equating total volume of training, total work, and total training time. Moreover, although the weight does not vary in free weight exercise, the resistance torque and, therefore, the required muscular contraction, does vary according to the mechanics of the specific exercise. Weight machines, on the other hand, operating through, e.g., a cam, enable variable resistance throughout the range of motion of an exercise. This is an attempt to approximate the strength curve of the exercise, thus forcing the muscle to contract maximally throughout the range of movement.

A barbell squat is a free weight, closed kinetic chain exercise involv-
ing muscles working across multiple joints. Athletes, using resistance training, often include a barbell squat program to improve lower extremity strength. Several studies have investigated the effect of a barbell squat exercise program on strength and athletic performance (8,12,25).

Weight machine exercises, using muscles working across only single joints in an open kinetic chain, are also commonly used to improve lower extremity strength.

In recent years, magnetic resonance imaging is finding increased use in basic muscle research (2,3,18). Previous work by Tesch (25), who used magnetic resonance imaging technology to investigate the thigh muscle activity in different lower extremity weight training exercises, identifies the quadriceps and adductor muscles as activated during a barbell squat. Likewise, activation of the quadriceps and adductor muscles can be attained through single joint, weight machine exercises (23). Thus, the purpose of this study was to compare a 6-week training program of closed kinetic chain barbell squats vs. open kinetic chain weight machine exercises for knee extension and hip adduction regarding barbell squat performance, isokinetic knee extension strength, and vertical jump height.

METHOD

Subjects

Sixteen male and eight female students, healthy and generally physically active with asymptomatic back, hip, and knee function, volunteered to participate in the study. The subjects were randomized into a closed and an open kinetic chain group. Due to illness and time constraints, three subjects (one male in each group and one female in the open kinetic chain group) failed to complete the study. Six subjects of the closed kinetic chain group and five subjects of the open kinetic chain group had previous experience with the barbell squat exercise and general weight training. The subjects' physical activity level was registered on a scale of 1–8 points, where 1 represented no physical activity and 8 represented engagement in competitive sports, as described by Engström (6). Subjects gave informed consent and were allowed to withdraw their participation at any time during the study. The study was approved by the Sahlgrenska University Hospital Ethics Committee.

Testing Procedures

Subjects were instructed and acquainted with the testing and training procedures orally and in writing prior to initial testing. All subjects were tested prior to training and at the completion of the training period. Three tests were used to evaluate the effects of training: 1) a barbell squat 3-repetition maximum test, 2) an isokinetic knee extension 1-repetition maximum test, and 3) a vertical jump test.

In the barbell squat 3-repetition maximum test, the subject made three consecutive repetitions of lowering the maximum weight possible until the thighs were parallel to the floor and then raised the body to an erect position with an Olympic barbell on the shoulders. The 3-repetition maximum for each subject was determined by the ability to complete three repetitions while maintaining correct depth and technique of the squat. The weight lifted was incremented by 2.5–10 kg until failure. The second testing session, after completion of the weight training period, started with six repetitions at 50% of the subject’s initial 3-repetition maximum result, followed by three repetitions at 75% and 100%, respectively. The test was then continued until failure. Two minutes of rest was allowed between trials. A board (2 cm thick) elevating the heels of the subject, thus facilitating a squatting position, as well as a tightly worn weight belt supporting the trunk were mandatory. The subject was instructed to keep the back upright with the feet at approximately 20° of external rotation, shoulder width apart. One test leader, positioned at the side of the subject, monitored that correct depth and technique of the squat were maintained. The other test leader spotted the subject from behind, hands placed around the waist of the subject during the lift in case of failure, using strong, aggressive verbal commands and encouragement. A mirror, placed 2 m in front of the subject, enabled visual feedback. A safety squat rack was used to ensure a safe performance. Prior to testing, the subject performed a warm-up of 10 minutes of ergometer cycling and two submaximal sets of 15 repetitions of the barbell squat. The mean number of trials performed by subject groups was calculated. The barbell squat 3-repetition maximum test and the isokinetic knee extension 1-repetition maximum test were separated by 24–72 hours at both testing occasions.

The isokinetic knee extension 1-repetition maximum test was performed using a Kinematic Communicator II dynamometer (Kin-Com, Chattec Corp., Chattanooga, TN). After 10 minutes of ergometer cycling at 50 W resistance, the subject was positioned with a hip angle of 75° of flexion in the test chair. The axis of the knee joint was aligned with the axis of the Kin-Com dynamometer resistance arm, and the lower leg shin pad was secured at approximately 10 cm proximal of the lateral malleolus. The trunk, hip, and thigh were strapped down to ensure proper positioning and stabilization. After five to six submaximal concentric knee extensions of the right leg at an angle velocity of 60°/sec, the subject performed three maximal trials from 90° to 5° knee angle (0° being full knee extension). The highest peak torque value was documented. One minute of rest was allowed between each trial. Two subjects in the open kinetic chain group had previous experience with the barbell squat exercise and general weight training. The subjects' physical activity level was registered on a scale of 1–8 points, where 1 represented no physical activity and 8 represented engagement in competitive sports, as described by Engström (6). Subjects gave informed consent and were allowed to withdraw their participation at any time during the study. The study was approved by the Sahlgrenska University Hospital Ethics Committee.
chain group tested their left leg because of ACL surgery and discomfort, respectively. A research physical therapist conducted the dynamometer tests, unaware of the subjects' group affiliation. The verbal commands were standardized during testing, and knowledge of testing results was withheld until completion of all tests.

The vertical jump test was performed with the subject standing erect on a platform, quickly performing a countermovement and jumping for maximal height. A measuring tape, secured at a tightly worn belt placed around the subject's waist, was pulled through a loop in the platform when the subject performed a vertical jump, and the height was documented as described by Thomeé et al (24). Vertical jump height was defined as the highest value among four trials. The test was supervised by the test leaders, instructing and monitoring the subjects during all of the trials. The vertical jump test followed directly after the isokinetic knee extension 1-repetition maximum test at both testing occasions.

Training

The subjects performed maximal, progressive weight training twice a week on nonconsecutive days for 6 weeks (Table 1). Subjects were instructed and acquainted with the training exercises orally and in writing prior to the initial training session. Subjects were instructed on the proper technique of each exercise, i.e., the importance of mental concentration during the movement of the exercise and using a controlled movement on both the concentric as well as the eccentric phase of the exercise.

The closed kinetic chain group performed a barbell squat program, activating the quadriceps and adductor muscles of the thigh (23). The open kinetic chain group performed a weight machine knee extension and hip adduction program, activating the quadriceps and adductor muscles of the thigh separately. For each exercise, four sets of 8–12 repetitions were performed at a load of approximately 10-repetition maximum. The resistance was progressively increased during the training period as the subjects were instructed to increase the training load when 10 repetitions per set was attained. Rest between sets was set at 2 minutes in the closed kinetic chain group and 1 minute in the open kinetic chain group. Subjects in the closed kinetic chain group initially performed barbell squats at approximately 75% of the result of the barbell squat 3-repetition maximum test. The result of the barbell squat 3-repetition maximum test was the criteria for establishing the initial weight load in the open kinetic chain group and was then adjusted accordingly by a minimum of 5 kg.

To monitor strength improvements, the training load, as well as the number of sets and repetitions, was recorded by the subjects in a training log. The mean training load at the start and at the end of the training period and the mean training session participation were calculated in subject groups. The level of supervision was set at 50%. The subjects' presence at each training session was registered and the following session was noted in a common calendar.

Each training session began with a warm-up of 10 minutes of ergometer cycling and two submaximal sets of 15 repetitions of the exercises used in their respective program. After the training session, the subjects were instructed to perform stretching exercises of the lower extremities.

Statistical Analysis

Student's t tests for independent groups were used for comparison of difference scores between groups, and paired t tests were used for pre- and post-comparisons within groups. Means and standard deviations were calculated for all variables, except physical activity (ordinal), where median and interquartile ranges were computed. Additionally, the Mann-Whitney U test was used to compare the physical activity level of subject groups.

RESULTS

There were no significant differences between groups in physical activity level. The median score was six in both subject groups. The interquartile range was 2 and 2.5, respectively, in the closed and the open kinetic chain group. There were no significant differences between the remaining subjects in the two groups regarding age, height, or weight (Table 2). The results obtained in the six testing sessions are summarized in Table 3.

Significant improvements were observed in both groups in the barbell squat test. The closed kinetic chain group improved 31% (P = 0.0001), which was significantly (P = 0.0007) more than the 13% (P = 0.0001) improvement seen in the open kinetic chain group. No significant changes were seen in subject
DISCUSSION

The specificity of free weight and weight machine training is a critical issue, demanding accurate and sensitive tests to prove the superiority of one method over another. The present study incorporated three different types of tests to monitor the effects of training, including an isotonic multijoint, an isokinetic single joint and, a more functional test, the vertical jump.

Isotonic testing such as a barbell squat or a vertical jump, activating the stretch-shortening cycle (15), could be argued to be more valid than isokinetic testing when assessing sporting activities; however, the isokinetic knee extension test used in the present study, though not activating the stretch-shortening cycle, has advantages such as greater control over velocity of motion, technique, and extraneous movement, which facilitates measurement reliability and objectivity (1).

Although subjects were tested on each occasion by the same research physical therapist, ensuring consistent subject standardization, the isokinetic knee extension test was not sensitive to the large increases of training load (50% and 100%, respectively) observed in both groups. This supports the results of other studies (8,21,28) where isotonic weight training strength improvements did not transfer to isokinetic movement. Measuring isokinetic knee extension strength at the 10-repetition maximum would possibly more accurately have reflected the increases of training load, as subjects performed sets of 10 repetitions of the exercises used in their respective program during the weight training period. The velocity of the exercises performed during the training period was estimated and, as no speed-specific results of the isokinetic knee extension were expected, only one angular velocity (60°/sec) was chosen. The use of velocity spectrum testing is suggested (26); however, due to the test specificity phenomenon demonstrated in the present study, testing at several velocities would probably not have affected the results. Another possible reason for nonimprovements in the isokinetic knee extension test could be that no isokinetic training was performed, thus limiting the degree of motor learning. Furthermore, as opposed to the barbell squat and the vertical jump test, the subjects were not aware of the pretraining test result when performing the posttrain-

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<th>TABLE 3. Results of the barbell squat 3-repetition maximum, isokinetic knee extension 1-repetition maximum, and vertical jump tests.</th>
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* Knee extension test (N = 9).
1 Intragroup difference (p = 0.0047).
2 Intragroup difference (p = 0.0001).
3 Difference in increase between groups (p = 0.0007).
ing test. This lack of feedback in the form of knowledge of previous results may to some extent explain why no group made significant gains in the isokinetic knee extension test.

The differences in increase of training load (50% and 100%, respectively) observed between groups may be due to greater demands when training with free weights. Thus, in the closed kinetic chain group, much time and effort was initially spent learning proper technique. Conversely, weight machines are probably less difficult to master, as they allow movement in only one plane and direction. Therefore, it is theorized that weight machines cause greater gains of training load in short-term weight training programs. According to Sale (19), increased performance as a result of weight training lasting less than 20 weeks is associated mainly with neural adaptation, such as increased motor unit activity of prime mover muscles and improved coordination, i.e., appropriate changes in the activation of synergists and antagonists. It is suggested that these two mechanisms may have contributed in different proportions in subject groups in the present study. The single joint weight machine exercises allowed a superior function of synergists and antagonists, enabling a high activation of motor units in prime mover muscles as opposed to the complex, multijoint free weight exercise where full motor activation probably was more difficult to achieve due to greater demands of coordination. Thus, the large gains of training load observed in the open kinetic chain group suggest that the nervous system learns how to use the muscles in an optimal way more rapidly when using weight machines as opposed to free weights.

Significant increases in the barbell squat 3-repetition maximum test were observed in both groups. Comparable results were reported by Hickson et al (12), who observed a 37% strength increase of a barbell squat 1-repetition maximum test in six subjects after 16 weeks of a barbell squat exercise program (five sets of 5-repetition maximum). The training load in the study by Hickson et al (12) was kept constant over the first 8 weeks and was then increased, as opposed to the present study where the resistance was progressively increased during the 6 weeks of training. Thorstensson et al (25) reported an increased mean barbell squat 1-repetition maximum strength by 67% in 14 male subjects after 8 weeks of a barbell squat exercise program (three sets of 6-repetition maximum). These improvements (mean 1-repetition maximum strength was 107 kg before and 179 kg after the training period) are remarkably large; however, little information of the testing procedure was provided.

Resistance training has been proven to increase motor performance tests (e.g., a vertical jump) involving movement at maximal speeds with little resistance. Colliander and Tesch (4) observed an 8% increase of vertical jump height in 11 subjects after a 12-week isokinetic weight training period, which is comparable with the 10% improvement by the closed kinetic chain group seen in the present study.

A comprehensive evaluation of the effects of training in the present study is limited by the lack of a control group as well as by the moderate length of the weight training period. Moreover, although not significant, the mean pretraining results of the three tests were higher in the open than in the closed kinetic chain group. Only about every other session was supervised. Repeated testing was not conducted; however, great importance was attached to the standardization of the tests as well as the training procedures. Further, the barbell squat test (4), the isokinetic knee extension test (22), and the vertical jump test (28) are proven reliable in the literature. The number of sets and repetitions performed by the groups as well as the time of rest between sets was based on clinical experience, with the intent of creating matching training conditions.

More research is needed to determine the effect of different training interventions on strength and power performance as well as to further develop the protocols and dynamometry employed in assessment.

CONCLUSION

The present study concludes that 6 weeks of closed kinetic chain weight training resulted in larger improvements in a barbell squat 3-repetition maximum and a vertical jump test than did open kinetic chain weight training. No significant changes were seen in subject groups in the isokinetic knee extension 1-repetition maximum test. The results may be explained by neural adaptation, weight training mode, and specificity of tests.

A large increase of training load was observed in both subject groups; however, improvements in isometric strength did not transfer to the isokinetic knee extension 1-repetition maximum test. Therefore, various forms of dynamometry, incorporating more functional performance tests, could be recommended when designing a resistance training study.

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4. Colliander EB, Tesch PA: Effects of eccentric and concentric muscle actions
Ability of closed and open kinetic chain tests of muscular strength to assess functional performance

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The purpose of this study was to investigate the ability of closed and open kinetic chain tests of muscular strength to assess functional performance. Sixteen healthy male subjects, with a mean (±SD) age, body mass and height of 27±5 years, 78±9 kg and 183±9 cm, respectively, volunteered to participate in the study. In the closed kinetic chain test (involving muscles working across multiple joints), the subjects performed a 3 repetition maximum (3 RM) barbell squat. The open kinetic chain test (involving muscles working across a single joint) consisted of a concentric isokinetic knee extension at an angular velocity of 60°/s, and was performed using a Kinetic Communicator II dynamometer. The test of functional performance (vertical jump) was performed with the subject standing erect, quickly performing a countermovement jump for maximal height. Moderately strong significant (P<0.05) correlations between the test of functional performance and the closed and open kinetic chain tests of muscular strength were noted, r=0.51 and r=0.57, respectively. It is suggested that the effect of training or rehabilitation interventions should not be based exclusively on tests of muscular strength. Rather, various forms of dynamometry including functional performance tests could be recommended.

Today, resistance exercise training plays a vital role in most athletic and rehabilitation programs. Except for sports like weight lifting, power lifting, and bodybuilding where the sole purpose is to enhance muscular strength and power, it is also believed among sports coaches and physical therapists that resistance training will result in improvements in functional performance such as jumping, throwing or running.

Tests of muscular function are commonly performed to assess functional performance, both in the sporting and the rehabilitation fields (Abernethy et al. 1995). However, the relationship between tests of muscular function and functional performance is still not clear. Yet, tests of strength and power are often used to monitor training-induced changes in performance or the effectiveness of rehabilitation. For example, Østerås et al. (1998) used a rehabilitation protocol following surgery of the anterior cruciate ligament (ACL) where they recommended quadriceps muscle torque force corresponding to 85% of the muscle strength, compared with the non-operated limb, before no restrictions needed be taken in sport and work activities. Recent studies, however, indicate a relatively low relationship between tests of muscle function and dynamic performance, both in healthy subjects (Murphy & Wilson 1997, Wilson et al. 1997) as well as in subjects with ACL-reconstruction (Pfeiffer & Banzer 1999). Pincivero et al. (1997) studied the relationship between concentric isokinetic quadriceps and hamstring strength values with the single hop for distance, a functional activity. It was concluded that only low to moderate significant relationships existed between the single hop for distance and the knee strength tests.

Currently, isometric, isokinetic and isotonic dynamometry are used to assess muscular function. Each form has its drawbacks, the main argument against isometric assessment being that isometric tests bear little resemblance to the dynamic nature of most sporting activities (Ashley & Weiss 1994). The perceived disadvantage of isokinetic assessment is the absence of acceleration and stretch-shortening cycle, and that single-joint, isolated assessment often is used, which again bears little resemblance to functional performance (Augustsson et al. 1998). Those against isotonic assessment tend to emphasize poor reliability and objectivity due to intersubject, intertrial and interlaboratory variations (Abernethy et al. 1995). Regardless of which of the three modes of dynamometry is employed, assessment can be performed using either closed or open kinetic chain movement.

A barbell squat is a free weight, closed kinetic chain exercise, involving muscles working across
multi-joint exercises. Athletes, using resistance training, often include a barbell squat program to improve lower extremity strength. Several studies have used a barbell squat test to determine the effect of various training and rehabilitation interventions (Wilson et al. 1997, Hickson et al. 1994). Isokinetic or isotonic testing and training such as knee extension/flexion, using muscles working across only single joints in an open kinetic chain, are also commonly used to evaluate and improve lower extremity strength (Thomeé et al. 1995, Fry et al. 1991).

In recent years, the importance of using closed kinetic chain evaluation (Greenberger & Paterno 1995) and rehabilitation (Beynnon et al. 1997) has been stressed, due to the belief that closed as opposed to open kinetic chain movement is more closely related to function. Moreover, several authors suggest that some types of open kinetic chain exercise are associated with greater anterior-posterior shear forces (Bynum et al. 1995, Yack et al. 1993) and patellofemoral compression forces (Bynum et al. 1995) compared to other types of closed kinetic chain exercise. However, few studies have compared the ability of closed and open kinetic chain tests of muscular strength to assess functional performance. Thus, the purpose of this study was to assess the relationship between a closed kinetic chain test of lower extremity strength and an open kinetic chain test of knee extensor strength with a test of functional performance.

Method

Subjects

Sixteen male subjects, healthy and generally physically active with asymptomatic back, hip and knee function, volunteered to participate in the study. Their mean (±SD) age, body mass and height were 27±5 years, 78±9 kg and 183±9 cm, respectively. Nine subjects had previous experience of the barbell squat exercise and of general weight training. The subjects' physical activity level was registered on a scale of 1–8 points, where 1 represented no physical activity and 8 represented engagement in exercise and of general weight training. The subjects' physical activity level score was 6 in the subject group and 8 in the control group.

Nine subjects had previous experience of the barbell squat exercise. All subjects were informed of the procedures orally and in writing prior to testing. Subjects were instructed and acquainted with the testing procedures.

Testing procedures

In the closed kinetic chain test, subjects performed a barbell squat 3 repetition maximum (3 RM): three consecutive repetitions of lowering the maximum weight possible until the thighs were parallel to the floor, and then raised to an erect position, with an Olympic barbell on the shoulders. The 3 RM for each subject was determined by the ability to complete 3 repetitions while maintaining correct depth and technique of the squat. The weight lifted was incremented by 2.5–10 kg until failure. Two minutes' rest was allowed between trials. A board (2 cm thick) elevating the heels of the subject, thus facilitating a squatting position, as well as a tightly worn weight-belt supporting the trunk were mandatory. The subject was instructed to keep the back upright with the feet at approximately 20° of external rotation, shoulder width apart. One test leader, positioned at the side of the subject, monitored that correct depth and technique of the squat was maintained. The other test leader spotted the subject from behind, hands placed around the waist of the subject during the lift in case of failure, using strong verbal commands and encouragement. A mirror, placed 2 m in front of the subject, enabled visual feedback. Prior to testing the subject performed a warm-up of 10 min of ergometer cycling and two submaximal sets of 15 repetitions of barbell squat. A safety squat rack (Squat Rack BL 101920, Competition Line, Borås, Sweden) and an Olympic 20 kg barbell with free-weight plates and collars (Casall, Norrköping, Sweden) were used. The barbell squat 3 RM test and the concentric isokinetic knee extension test were separated by 24–72 h.

The open kinetic chain test (concentric isokinetic knee extension) was performed using a Kinetic Communicator II dynamometer (Chattanooga Group, Inc., P.O. Box 489, Hixson, TN 37343, USA). After 10 min of ergometer cycling at 50 W resistance, the subject was positioned with a hip angle of 75° of flexion in the test chair. The axis of the knee joint was aligned with the axis of the Kin-Com dynamometer resistance arm and the lower leg shin pad was secured at approximately 10 cm proximal to the lateral malleolus. The trunk, hip and thigh were strapped down to ensure proper positioning and stabilization. After 5–6 submaximal concentric knee extensions of the right leg at an angular velocity of 60°/s, the subject performed 3 maximal trials from 90° to 5° knee angle (0° being full knee extension). The highest peak torque value was documented. One minute of rest was allowed between each trial. One subject tested his left leg because of discomfort. A research physical therapist conducted the dynamometer tests.

The test of functional performance (vertical jump) test was performed with the subject standing erect on a platform, quickly performing a countermovement jump for maximal height. A measuring tape, secured at a tightly worn belt placed around the subject's waist, was pulled through a loop in the platform when the subject performed a vertical jump and the height was documented, as described by Thomeé et al. (1995). Vertical jump height was defined as the highest value among 4 trials. The test was supervised by the test leaders, instructing and monitoring the subjects during all the trials. The vertical jump test followed directly after the concentric isokinetic knee extension test.

Statistical analysis

To examine the relation between the values of the closed and open kinetic chain tests of muscular strength with the test of functional performance, Pearson product-moment correlation coefficients were determined. Relationship differences between the closed and open kinetic chain tests of muscular strength variables were then computed using two-tailed t test for testing differences between two dependent correlation coefficients (Guilford & Fruchter 1973). The significance was considered at the α level of P<0.05.

Results

The mean (±SD) barbell squat 3 RM strength, concentric isokinetic knee extension torque and vertical jump height were 101±18 kg, 241±65 Nm and 54±7 cm, respectively.
Relation between muscular strength and functional performance tests

Moderately strong significant ($P<0.05$) correlations between the test of functional performance and the closed and open kinetic chain tests of muscular strength were noted, $r=0.51$ and $r=0.57$, respectively. Fig. 1 illustrates the correlations between closed and open kinetic chain test scores and the test of functional performance. There was also a moderately strong significant ($P<0.01$) correlation between the closed and the open kinetic chain test of muscular strength, $r=0.64$.

Closed and open kinetic chain relationship differences

When comparing the coefficients of correlation ($r=0.51$ and $r=0.57$) between the tests of muscular strength and functional performance, it was found that this relationship was not significantly different ($t=0.70, P>0.05$).

Discussion

We investigated the ability of closed and open kinetic chain tests of muscular strength to assess functional performance. Moderately strong significant ($P<0.05$) correlations were noted between the test of functional performance and the closed and open kinetic chain tests of muscular strength, $r=0.51$ and $r=0.57$, respectively. A correlation of $r=0.64$ ($P<0.01$) was obtained between the closed and the open kinetic chain test of muscular strength.

The fact that the closed and open kinetic chain tests of muscular strength did not differ in regard to their ability to predict performance probably reflects that the quadriceps muscle is important in vertical jumping and that, furthermore, individual quadriceps muscle strength correlates with gluteus maximus muscle and triceps surae muscle strength.

In a recent study by Blackburn & Morrissey (1998), open kinetic chain knee extensor strength demonstrated startlingly low correlation with vertical jump ($r=0.01$) and standing long jump ($r=0.07$) performance, whereas Petschnig et al. (1998), who studied the relationship between an isokinetic quadriceps strength test and four different functional performance tests in healthy subjects and patients with surgery of the ACL, reported moderately strong correlation coefficients (between $r=0.45$ and $r=0.55$). In a review (Abernethy et al. 1995) of articles where correlations between muscular strength tests and functional performance were investigated, relationships typically ranged between $r=0.50$ and $r=0.93$.

Östenberg et al. (1998) recently reported low correlations between isokinetic knee extensor strength and functional tests in healthy female soccer players and recommended not using functional performance and isokinetic testing interchangeably. Murphy & Wilson (1997) went even further, suggesting the effectiveness of training or rehabilitation programs should be based on changes in performance rather than tests of muscular function. However, the restoring of muscle size and strength is a cornerstone in rehabilitation, and therefore tests of muscular function must be considered essential. In a recent study (Pfeifer & Banzer 1999), pronounced strength deficits over a long period of time after surgery on the ACL was noted. Likewise, Carter & Edinger (1999) were intrigued to find only half of the competitive athletes in their study had achieved 80% or greater leg strength of the ACL-operated leg by six months after surgery, as it is now customary to allow return to full activities at that time, with some authors advocating return to sports as early as four months after the procedure
References


Beynnon B, Johnson R, Fleming B, Carter & Edinger (1999) concluded that athletes theoretically may return to sports four to six months postoperatively, but that frequently leg strength is not adequate at that time to do so without running the risk of reinjuring the knee. This is supported by Johnston et al. (1998), who investigated the effect of lower extremity muscular fatigue on motor control performance. It was concluded that fatigued individuals are at increased risk of injury because of loss of balance and that preconditioning may prevent injury.

Both closed and open kinetic chain testing could under certain circumstances be considered as having low validity. As a diagnostic test, a closed kinetic chain movement, involving several groups of muscles working across multiple joints, is unable to determine to what extent a particular muscle is activated. Conversely, the open kinetic chain test, because of its more “non-functional” nature, is able to isolate a specific muscle and thereby detect dysfunction. Thus, the purpose of assessment should determine which mode of dynamometry be used: to identify specific deficiencies or problem areas, open kinetic chain testing would be preferred, whereas a closed kinetic chain test may be better suited for assessing functional performance.

Despite several studies (Beynnon et al. 1997, Yack et al. 1993) concerning safety issues of closed and open kinetic chain exercises in ACL rehabilitation, and although some authors have advocated the sole use of closed kinetic chain exercises (Bynum et al. 1995, Shelbourne & Nitz 1992), it is concluded that both types of exercises can be performed in ways that do not place excessive strain on the ACL (Fitzgerald 1997). Escamilla et al. (1998), comparing knee joint biomechanics while performing closed and open kinetic chain weight training at a 12 RM load, reported that peak ACL tension forces in open kinetic chain exercise were only 0.2 times bodyweight, and nonexistent in closed kinetic chain exercise. Factors such as joint compressive forces (e.g. axial loading) and joint geometry probably play integral roles in knee joint stability during closed kinetic chain exercise (Isear et al. 1997), whereas significant coactivation of the antagonists during maximal knee flexion/extension, indicating an inhibitory mechanism which prevents overloading of the joint and contributes to joint stabilization (Kellis & Baltzopoulos 1998), would explain the low ACL tension forces during open kinetic chain exercise.

There are some methodological issues to be addressed. The sample size in the present study was moderate, but for our purposes we believed it was adequate. No definitive answers regarding the exact correlation between tests of muscular strength and functional performance could be achieved from the present study. Our results are nevertheless of importance due to the scarcity of data in the literature on the ability of closed and open kinetic chain tests of muscular strength to assess functional performance.

More research is needed to further improve protocols and dynamometry employed in the assessment of training or rehabilitation interventions. A challenge for future research could be to develop tests sensitive and specific enough to discriminate relevant muscular and functional deficits or compensations following, for example, ACL-reconstruction. We believe a testing procedure that combined muscular strength with functional performance parameters would enhance the diagnostic spectrum and provide a more comprehensive assessment. For example, functional performance ought to be tested under both fatigued and nonfatigued conditions. This presumably would improve the possibilities to evaluate and compare muscular function of the healthy and injured leg.

In conclusion, the moderate correlations between tests of muscular strength and the vertical jump test indicate that the results of strength measurements cannot be used to adequately assess functional performance. Consequently, it is suggested that the effect of training or rehabilitation interventions should not be based exclusively on tests of muscular strength. Rather, various forms of dynamometry including functional performance tests could be recommended.

Key words: barbell squat; isokinetic knee extension; vertical jump; multi-versus isolated-joint testing; rehabilitation.

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Study III
Effect of Pre-Exhaustion Exercise on Lower-Extremity Muscle Activation During a Leg Press Exercise

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ABSTRACT

The purpose of this study was to investigate the effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise. Pre-exhaustion exercise, a technique frequently used by weight trainers, involves combining a single-joint exercise immediately followed by a related multijoint exercise (e.g., a knee extension exercise followed by a leg press exercise). Seventeen healthy male subjects performed 1 set of a leg press exercise with and without pre-exhaustion exercise, which consisted of 1 set of a knee extension exercise. Both exercises were performed at a load of 10 repetitions maximum (10RM). Electromyography (EMG) was recorded from the rectus femoris, vastus lateralis, and gluteus maximus muscles simultaneously during the leg press exercise. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was also documented. The activation of the rectus femoris and the vastus lateralis muscles during the leg press exercise was significantly less when subjects were pre-exhausted (p < 0.05). No significant EMG change was observed for the gluteus maximus muscle. When in a pre-exhausted state, subjects performed significantly (p < 0.001) less repetitions of the leg press exercise. Our findings do not support the popular belief of weight trainers that performing pre-exhaustion exercise is more effective in order to enhance muscle activity compared with regular weight training. Conversely, pre-exhaustion exercise may have disadvantageous effects on performance, such as decreased muscle activity and reduction in strength, during multijoint exercise.

Key Words: alternative weight training technique, electromyography, single-joint exercise, multijoint exercise

Introduction

In the initial stages of weight training for sports or rehabilitation purposes, increases in strength are quite rapid, mainly because of neural adaptation (17). In contrast, at the intermediate and advanced stages of weight training progress is markedly slower. By then, weight training for athletic purposes is often characterized by performance plateaus or even decrements (3, 4). However, a number of empirically based strategies have been developed through the years to maintain a positive response to long-term weight training (2, 13). Thus various systems, such as periodization (i.e., organization of training into distinct periods), and methods, such as supersets, forced reps, power factor training, and pre-exhaustion exercise, are used to avoid performance to plateau and for bringing about optimal gains in strength and muscle hypertrophy (1–3, 18, 20–22).

The practice of pre-exhaustion exercise has been made popular by Eastern European weight lifters and by body builders in the United States (2). Pre-exhaustion exercise involves working a muscle or a muscle group to the point of fatigue using a single-joint exercise, immediately followed by a related multijoint exercise (2, 18, 21). For example, a weight trainer might pre-exhaust his or her quadriceps muscles by performing a knee extension exercise, then follow that exercise immediately with either a barbell squat exercise or a leg press exercise (2). In nonscientific weight training literature, authors advocate this method to overcome “sticking points” or for “bringing a ‘weak’ body part up to speed” by providing the pre-exhausted muscle with a greater training stimulus compared with regular weight training (12).

The effects of fatigue on muscle function and the implications of this on strength and muscle hypertrophy acquisition is not well documented, and existing
data on whether fatigue may stimulate strength and muscle volume development is contradictory. Rooney et al. (16) reported that fatiguing, continuous repetitions resulted in greater strength gains compared with when rest was taken between repetitions. Similarly, Schott et al. (19) demonstrated greater strength gains and muscle hypertrophy following strength training using long, fatiguing activations compared with short, intermittent activations. Also, Tesch (22) noted that body builders, who display large muscularity and mass, must “punish themselves” (i.e., perform sets to exhaustion in their training programs) in order to see progress. Conversely, Pincivero et al. (15) examined the influence of rest intervals on strength gains subsequent to high-intensity training and reported that a longer rest period between sets resulted in greater improvement in muscle strength. The results obtained by Pincivero et al. (15) is supported by the observation that development of fatigue is not desired in power lifting where the major training goal is to optimize maximal strength (2). Taken together, it is still not clear whether accumulation of fatigue during exercise may be of importance if the objective is to bring about maximal muscle hypertrophy and strength gains.

Although weight trainers frequently use pre-exhaustion exercise, this training technique has, to our knowledge, not been the subject of a scientific study. Weight trainers using this method believe pre-exhaustion exercise would result in greater muscle activation for the subsequent multijoint exercise because presumably the pre-exhausted muscle is engaged in both exercises (12). To test this hypothesis, we decided to use the knee extension and the leg press as test exercises to gain a stress profile of the pre-exhaustion method and to compare this technique to regular weight training. Thus the purpose of this study was to investigate the effect of pre-exhaustion exercise on lower-extremity muscle activation during a leg press exercise.

Methods

Experimental Approach to the Problem

To test the hypothesis presented in the Introduction, electromyography (EMG) was recorded from 3 lower-extremity muscles with and without pre-exhaustion exercise (knee extensions) during the leg press exercise. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was also documented. The collection of these acute data may suggest whether pre-exhaustion exercises have a greater potential for producing strength and muscle size gains compared with regular weight training.

Subjects

Seventeen healthy male subjects with a mean (±SD) age, body mass, and height of 26 ± 4 years, 77 ± 6 kg, and 182 ± 6 cm, respectively, volunteered to participate in the study. All subjects were recreational weight trainers with an average (±SD) of 5.5 ± 4 years of resistance training experience. None of the subjects had a recent or remote history of significant lower-extremity injury. Before participation in this study, each subject provided informed consent approved through the Ethics Committee of the Faculty of Medicine, Göteborg University, Sweden.

Determination of 10 Repetitions Maximum

Each subject performed a pretest 4 to 5 days before testing began. At this time the experimental protocol was reviewed and the subjects were given the opportunity to ask questions. In addition, each subject’s 10 repetitions maximum (10RM) was determined for a knee extension exercise and a leg press exercise by using the maximum weight that could be lifted for 10 consecutive repetitions. The weight lifted for each trial was incremented by 5–10 kg until failure occurred. Each subject’s knee-flexing and knee-extending cadence was not fixed during the knee extension and the leg press exercise, rather each subject was allowed to use a self-selected tempo while performing the exercises. Five minutes of rest was allowed between trials.

EMG Electrode Preparation

The exercise session began with EMG electrode preparation. Each electrode site was shaved, abraded, and cleaned with alcohol to facilitate electrode adherence and conduction of EMG signals. Bipolar surface electrodes with a diameter of 9 mm (Red Dot, 3M Medica, Borken, Germany) were placed over the bellies of the rectus femoris, vastus lateralis, and gluteus maximus muscles using a standardized method described by Isræl et al. (10).

A Tubigrip (Seaton Healthcare Group, Oldham, England) compression wrap was applied to the test extremity (right leg) to maintain electrode placement. Heavy adhesive tape was used to secure electrode placement on the gluteus maximus muscle. All test sites were identified and prepared by the same investigator.

Instrumentation

The EMG signal was preamplified with a gain of 1,000, an impedance of more than 0.5 MOhm at 50 Hz, and a band width of 0.5–400 Hz by an HDX-82 (Chattanooga Group Inc., Hixson, TN) and was thereafter band pass-filtered between 7 and 490 Hz by a KC-EMG (Chattanooga Group). The EMG was sampled with a frequency of 1,250 Hz by an NB-MIO-16L9 (National Instruments Corporation, Austin, TX) on a Macintosh computer with software developed in Lab View (National Instruments) by Punos Electronics AB, Göteborg, Sweden. The EMG signal was rectified and the average of the amplitude was calculated using the root mean square (RMS) method. During testing, RMS EMG signals were monitored on the computer. Before
Effects of Pre-Exhaustion Exercise on Muscle Activation

muscle—seated with the hip at 90° and the knee at 60° of flexion; and the gluteus maximus muscle—prone with the hip at 10° of extension and the knee at more than 90° of flexion. Each activation was held for 4 seconds with a 10-second rest period between repetitions. Each EMG sample included the entire MVIA interval of 4 seconds’ duration. The largest RMS value of the 3 MVIAs was designated the reference EMG and used for normalization.

The Pre-Exhaustion Exercise Procedure
Subjects were then placed in the knee extension and leg press station (Figure 1). Before testing commenced, each subject was instructed in the proper technique for each exercise (i.e., the importance of mental concentration during the performance of the exercise) and using a controlled movement for both the concentric as well as the eccentric phase of the exercise. Warm-up consisted of 2 submaximal (not in excess of 40% of their 10RM pretest weight) sets of 10 repetitions of the knee extension and leg press exercises.

The starting and ending positions for the knee extension exercise were seated with approximately 120° knee flexion angle. From the starting position, each subject extended the knees and returned to the starting position. The pad supporting the back was adjusted for each subject so that the axes of the knee joints were aligned with the axis of the knee extension machine resistance arm. The footpad was positioned at approximately 5 cm proximal to the lateral malleolus.

The beginning and ending position for the leg press was with the knee in full extension. Subjects were assisted to the beginning position of the leg press exercise by 1 investigator; thus in this position data collection was initiated. In a continuous motion the subject descended to maximum knee flexion (120°) and then ascended back to the starting position. Visual feedback of the 120° knee flexion angle position for each subject was enabled through markers, which were attached onto the leg press machine. Subjects used a standardized 40-cm stance width on the leg press platform, with the feet at 20° of external rotation.

Subjects performed 1 set of pre-exhaustion exercise of the quadriceps muscles to the point of fatigue using the knee extension exercise at a load of 10RM. Immediately following that exercise, EMG was recorded from the rectus femoris, vastus lateralis, and gluteus maximus muscles simultaneously during 1 set of the leg press exercise performed at a load of 10RM. After a 20-minute rest period, EMG was recorded as subjects once again performed 1 set of the leg press exercise (without pre-exhaustion exercise) at a load of 10RM. Subjects terminated the exercise sets on the completion of 10RM or muscle failure. One investigator monitored the exercise to ensure that the correct technique was maintained while using strong verbal commands and encouragement. EMG samples were collected for all repetitions of the leg press exercise set. The range of motion for collecting the EMG was from 0° to 120° knee flexion, and both the concentric and the eccentric phases of the exercise were examined. The mean RMS value for the leg press exercise set under each condition was then calculated. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was documented. The order of performing the leg press exercise (with and without pre-exhaustion exercise) was randomly assigned for subjects. Prior to testing all subjects performed a pre-exhaustion exercise procedure session for familiarization purposes, with a minimum of 4 days between tests.

Statistical Analyses
Muscle activation amplitude obtained during the pre-exhaustion exercise procedure was normalized relative to the MVIA (test EMG amplitude/EMG amplitude of MVIA multiplied by 100). Paired-samples t-test was used to compare the average RMS values collected during the leg press exercise with and without pre-exhaustion exercise. The number of repetitions of the leg press exercise performed by subjects with and without pre-exhaustion exercise was compared using

Figure 1. Testing setup: Subjects performed a knee extension exercise (pre-exhaustion) immediately followed by a leg press exercise. Both exercises were performed at a 10 repetition maximum (10RM) load.
a paired-samples t-test. An alpha level of 0.05 was used for all comparisons.

**Results**

Significantly lower EMG activity during the leg press exercise set was noted for the rectus femoris ($p = 0.001$) and the vastus lateralis ($p = 0.034$) muscles with pre-exhaustion exercise compared to without pre-exhaustion exercise. No significant difference of gluteus maximus muscle activity was observed between the pre-exhausted condition and the non-pre-exhausted condition ($p = 0.755$; Figure 2). Subjects performed significantly ($p = 0.001$) less repetitions of the leg press exercise with compared to without pre-exhaustion exercise; the mean ($\pm SD$) number of repetitions was 7.9 ($\pm 1.4$) and 9.3 ($\pm 2.3$), respectively.

**Discussion**

Our study showed that pre-exhaustion exercise had the exact opposite effect on muscle activation as suggested by weight trainers using this technique. In our study, pre-exhaustion exercise (a single-joint knee extension exercise) resulted in decreased, rather than increased, activation of the quadriceps muscle during a multijoint leg press exercise. Subjects also performed less repetitions of the leg press exercise when in a pre-exhausted state. Thus the lower muscle activity and reduction of strength when using pre-exhaustion exercise compared with regular weight training implies the pre-exhaustion technique may be less effective in muscle development and strength acquisition.

By using pre-exhaustion exercise the muscle activity, in theory, may increase, as studies have demonstrated that EMG activity consistently increases during exercise performed at a constant load (6, 7, 14). However, this was not the case in our study, as pre-exhaustion exercise of the knee extensor muscles resulted in decreased EMG amplitude of the rectus femoris and vastus lateralis muscles during the leg press exercise. One possible explanation for this result might be muscle substitution, i.e., that the fatigue of the quadriceps muscle may have dictated greater use of synergistic muscle. Although our data showed no significant change of gluteus maximus muscle activation as a result of pre-exhaustion exercise, it is possible that there was different activation of other hip extensors, such as the adductor muscles, or plantar flexion muscles, such as the gastrocnemius (which also has potential function at the knee) and soleus muscles.

Another method of pre-exhaustion described in the literature involves fatiguing synergistic or stabilizing muscles, rather than prime mover agonistic muscles, before performing the primary exercise movement (2). An example of this strategy is performing lat pull-downs or military presses prior to performing the bench press exercise. It is theorized that the fatigued smaller muscles will contribute less to the movement of the later exercises, thereby placing greater stress on the large muscle groups (2). Our data, where the fatigued knee extensor muscles contributed less during the subsequent leg press exercise, support the idea of pre-exhausting small synergistic muscles, rather than prime mover agonistic muscles. Therefore, to meet the goal of increased quadriceps muscle activity during a leg press exercise, we speculate that pre-exhaustion ex-
exercise should consist of a hip extension exercise, rather than a knee extension exercise. Theoretically, this would force the quadriceps muscles to increased activity because the synergistic hip extensor muscles would probably contribute less during the leg press exercise. However, the advantages and disadvantages of different pre-exhaustion exercise combinations in optimizing strength and muscle size need further study.

The vastus lateralis muscle demonstrated higher EMG activity than that of the rectus femoris muscle during the leg press exercise both when subjects were in a non-fatigued and a fatigued state (−75% vs. −100% of MVIA; Figure 2). We believe that this different EMG amplitude pattern represents the biarticular nature of the rectus femoris muscle, which also functions at the hip joint. This requires the rectus femoris muscle to decrease its activity since the rectus femoris muscle is a hip flexor, not a hip extensor.

Subjects performed significantly \( p < 0.001 \) less repetitions of the leg press exercise when in a pre-exhausted state. This is in accordance with the observations of Fleck and Kraemer (2) who compared the workout logs of subjects when barbell squats were placed in the beginning of the workout with those when squats were placed at the end of the workout. Significantly heavier resistances were used when squats were performed first.

Although no training studies have been performed on the effects of pre-exhaustion exercise, it appears unlikely, based on the acute stresses measured in our study, that pre-exhaustion exercise would result in greater gains in muscle strength or hypertrophy than regular weight training.

Although most weight trainers use a multiple-set system when performing the pre-exhaustion method, only 1 set of each exercise was used experimentally in our study. A multiple-set protocol would not have allowed sufficient recovery from prior pre-exhaustion and non-pre-exhaustion exercise sets to allow an accurate comparison between conditions.

The movement velocity during the knee extension exercise was not controlled in our study. This is due to the fact that the cadence consistently decreases from the first to the last repetition for a subject during a set of heavy weight training exercise (11).

When applied to the quadriceps muscle, the pre-exhaustion technique involves a knee extension exercise combined with either a leg press or a barbell squat exercise (2). The weight machine leg press exercise was preferred in our study because of advantages such as greater control over technique and extraneous body movement (5), which may have facilitated measurement reliability and objectivity. The free weight barbell squat exercise could be considered more of an overall body movement, and is in addition probably more difficult to perform correctly due to greater demands for coordination and balance (5).

Empirically, the resistance used when performing pre-exhaustion exercise is in the 10RM range. With the intent of reproducing normal training conditions, pre-exhaustion exercise sets in our study were therefore performed at a load of 10RM, which approximates 80% of 1RM strength (8, 9). Consequently, quadriceps muscle force fell to about 80% of maximal strength as a result of knee extension pre-exhaustion exercise. The use of different RMs (lighter or heavier resistance than 10RM) when performing pre-exhaustion exercise may have produced different results.

**Practical Applications**

Despite the widespread use of pre-exhaustion exercise by weight trainers as a technique to increase the activation of the targeted (fatigued) muscle during multi-joint exercise, pre-exhaustion exercise may have disadvantageous effects on muscle performance, i.e., decreased activation of the fatigued muscle. Also, subjects performed less repetitions of the leg press exercise when in a pre-exhausted state. Therefore our data imply that weight trainers using this method should reconsider its effectiveness in producing strength and muscle size gains.

Future research in this area should address the effect of a reversed pre-exhaustion strategy, as our data support the notion of pre-exhausting small synergistic muscles, rather than prime mover agonistic muscles.

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Study IV
Single-leg hop testing performed under fatigued conditions using pre-exhaustion exercise: reliability and biomechanical analysis

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Abstract

A pre-exhaustion exercise protocol was combined with single-leg hop testing to improve the possibilities to evaluate the effects of training or rehabilitation interventions. In the first test-retest experiment, 11 healthy male subjects performed two trials of single-leg hops under three different test conditions: nonfatigued and following pre-exhaustion exercise which consisted of unilateral weight machine knee extensions at 80% and 50%, respectively, of 1 repetition maximum (1 RM) strength. ICC coefficients ranged from 0.75 to 0.98 for different hop test conditions, indicating that all tests were highly reliable. For the second experiment, eight healthy male subjects performed the pre-exhaustion exercise protocol to investigate how fatigue influences lower-extremity joint kinematics and kinetics during single-leg hops. Hip, knee and ankle joint angles, moments and powers, as well as ground-reaction forces were recorded with a six-camera, motion-capture system and a force platform. Recovery of hop performance following the fatiguing exercise was also measured. During the take-off for the single-leg hops, hip and knee flexion angles, generated powers for the knee and ankle joints, and ground-reaction forces decreased for the fatigued hop conditions compared with the nonfatigued condition (P<0.05). Compared with landing during the nonfatigued condition, hip moments and ground-reaction forces were lower for the fatigued hop conditions (P<0.05). Absorbed power was two to three times greater for the knee than for the hip and five to ten times greater for the knee than for the ankle during landing for all test conditions (P<0.05). Most measured variables had recovered three minutes post-exercise. It is concluded that the pre-exhaustion exercise protocol combined with single-leg hop testing was a reliable method for investigating functional performance under fatigued test conditions. Further, subjects utilized an adapted hop strategy which employed less hip and knee flexion and generated powers for the knee and ankle joints during take-off, and less hip joint moments during landing under fatigued conditions. The large negative power values observed at the knee joint during the landing phase of the single-leg hop, during which the quadriceps muscle activates eccentrically, indicate that not only hop distance but also the ability to perform successful landings should be investigated when assessing dynamic knee function.

Key words: Functional testing, inverse dynamics, jumping
Introduction

The ability to perform work or sport activities under fatigued conditions (i.e. the ability to sustain muscular force and power) is of great importance. Moreover, injuries often tend to occur at the end of a sporting event, when a participant is fatigued (Dugan & Frontera, 2000; Feagin, Lambert, Cunningham, Anderson, Riegel, King, VanGenderen, 1987; Östenberg & Roos, 2000). However, tests of dynamic function for sports or rehabilitation purposes are generally performed under nonfatigued test conditions. For example, athletes or patients are generally not fatigued when performing tests such as single-leg hops or vertical jumps, and as a consequence, an indication of an individual’s physical-functional capabilities when in a condition of muscle fatigue is not always provided. To improve the possibilities to evaluate the effects of training or rehabilitation interventions, the testing of dynamic function under fatigued conditions has been suggested (Augustsson & Thomeé, 2000). However, assessing dynamic performance under fatigued test conditions is problematic; for one thing, because it requires a standardised method to quantify both the level and the progression, of fatigue.

Muscle fatigue research has focused primarily on issues such as energy supply (Sahlin, Tonkonogi, Söderlund, 1998), muscle co-activation (Weir, Keefe, Eaton, Augustine, Tobin, 1998) and mechanisms underlying the reduction of force in skeletal muscle fatigue (Westerblad, Allen, Bruton, Andrade, Lannergren, 1998), whereas the effect of muscle fatigue on functional performance, such as jumps or hops, has received little attention. The related issue concerning of whether muscle fatigue might affect postural balance has been studied with contradictory results (Johnston, Howard, Cawley, Losse, 1998; Adlerton & Moritz, 1996).

Studies of the biomechanical behaviours of the lower-extremity during take-offs and landings for different jumps and hops have been focused on the prediction of impact forces (Zhang, Bates, Dufek, 2000), comparisons of landing techniques (Devita & Skelly, 1992), and optimum take-off techniques (Seyfarth, Blickhan, van Ingen Schenau, 2000). Further, the contribution made by muscles acting across the hip, knee and ankle joints during the propulsive phase of different hop tests has been estimated (Jacobs, Bobbert, van Ingen Schenau, 1996), and the importance of the quadriceps muscle as a contributor during jumps for distance has been questioned (Pfeifer & Banzer, 1999; Pincivero, Lephart, Karunakara, 1997a; Robertson & Fleming, 1987; Östenberg, Roos, Ekdahl, Roos, 1998). However, we are not aware of any studies investigating the way fatigue influences the kinetic and kinematic take-off and landing performances during single-leg hops. Moreover, single-leg hops are used clinically to assess knee function in patients following knee injury or surgery, as it is thought that single-leg hops represent an activity which places high demands on the ability of the leg musculature to generate substantial knee joint
moment and power during the take-off (Rudolph, Axe, Snyder-Mackler, 2000). However, to our knowledge, no published studies have investigated absorbed power values for the knee during single-leg hop landings; an eccentric loading situation which we believe is equally demanding on knee function as take-offs. Further, research evaluating the recovery of functional performance, such as single-leg hop take-offs and landings, following fatiguing exercise, is limited.

The first aim was to develop, and to examine the reliability of, a single-leg hop test performed under standardised, fatigued conditions. The second aim was to obtain biomechanical information concerning the effect of a quadriceps muscle fatigue protocol on the kinetic and kinematic behaviour of the lower-extremity during single-leg hops. We hypothesised that when subjects were fatigued they would utilize an adapted hop strategy, and that the contribution made by the muscles acting across the hip, knee and ankle joints during take-off would differ depending on the hop test condition. The third aim of our study was to examine absorbed power values for the hip, knee and ankle joints during single-leg landings across test conditions. The fourth and final aim of our study was to investigate the recovery of hop performance following fatiguing exercise of the quadriceps muscle.

Methods
Subjects

The first experiment, which involved the development of a single-leg hop test performed under fatigued test conditions, using a test-retest design, included 11 male subjects, healthy and generally physically active with asymptomatic back, hip and knee function. Their mean (±SD) age, body mass and height were 27±5 years, 75±10 kg and 182±4 cm, respectively.

The second experiment, in which a biomechanical analysis was performed to investigate how fatigue influences lower-extremity joint kinematics and kinetics during single-leg hops, included eight male subjects, healthy and generally physically active with asymptomatic back, hip and knee function. Their mean (±SD) age, body mass and height were 31±6 years, 80±6 kg and 185±4 cm, respectively. The study was approved by the Human Ethics Committee at the Faculty of Medicine, Göteborg University, Sweden. Informed consent was obtained and the rights of subjects were protected.

Pre-test

For both experiments, each subject performed a hop test for familiarisation purposes and, in addition, a knee-extension 1 repetition maximum (1 RM) strength determination at a pre-test two to three days before the actual testing sessions. Functional performance was assessed by a single-leg hop test in which the subject was instructed to stand on one leg and to position his toes to a mark on the floor. The subject was then instructed to hop forward as far as possible
and to land on the same leg. The subject was allowed to swing his arms freely as he jumped. The distance, in centimeters, was measured from the toe in the starting position to the heel where the subject landed. A hop was only regarded as successful if the subject was able to keep his foot in place while balancing on one leg (i.e. no extra hops was allowed) until an investigator had marked where the subject had landed. Failure to do so resulted in a re-hop. The test was performed until three successful hops were obtained for each leg, with the starting order of the right or the left leg randomly assigned to the subjects. Each subject was given two practice trials before the test.

Thereafter, each subject’s unilateral 1 RM strength for the right and the left leg was determined for a knee-extension exercise by using the maximum weight that could be lifted for one repetition. Subjects were placed in a variable resistance knee-extension machine (Model Leg Extension FL 130, Competition Line, Borås, Sweden). Each subject was instructed by an investigator in the proper technique for the exercise. The subjects performed two submaximal warm-up sets of the knee-extension exercise. The starting and ending positions for the knee-extension exercise were seated with approximately 90° of knee flexion angle. From the starting position, each subject extended the knee until 0° of flexion angle and returned to the starting position. The pad supporting the back was adjusted so that the axis of the knee joint was aligned with the axis of the resistance arm. The footpad was positioned at approximately five cm proximal to the lateral malleolus. The weight lifted for each trial was incremented by 2.5-10 kg until failure occurred. One minute of rest was given between trials. The starting order of the right or the left leg was randomly assigned to the subjects.

**Experimental protocols**

All the subjects in the first experiment participated in two testing sessions to determine test-retest reliability of hop performance (measured as maximal hop length) during the different test conditions. Testing took place on two separate days with at least 72 hours between testing sessions. Hop performance was compared under three standardised test conditions: nonfatigued and immediately following fatiguing exercise of the quadriceps muscle at 50% and 80% of 1 RM-strength, respectively.

In order to standardise the fatiguing exercise, we used a fatigue protocol developed from previous work on healthy subjects (Augustsson, Thomeé, Hörnstedt, Lindblom, Karlsson, Grimby, 2003). This fatigue protocol consists of so-called “pre-exhaustion exercise”, which involves working a muscle to fatigue by performing as many repetitions in a single set as possible at a load of, for example, 80% of 1 RM, using a single joint exercise, after which that exercise is followed immediately by a multijoint exercise. By adopting the concept of pre-exhaustion exercise, and by using the RM continuum, we have constructed a
testing protocol that quantifies both the level and the progression, of muscle fatigue. Specifically, a “target force” of pre-exhaustion activations can be set at a given percentage of 1 RM-strength (for example, 80% of 1 RM) and in turn allow for any degree of muscle fatigue to be obtained in a controlled manner. Thus, if a subject performs as many repetitions as possible until failure with, for example, 80% of 1 RM, 1 RM-strength consequentially is reduced by 20%.

The pre-exhaustion exercise protocol consisted of performing consecutive unilateral knee extensions with a load of 50% and 80% of 1 RM, respectively, until failure occurred using a variable resistance knee-extension machine. Each subject began the testing by performing single-leg hops for the right and the left leg under nonfatigued conditions as previously described. Subjects then performed unilateral fatiguing knee extensions until failure occurred at 80% of 1 RM; the leg tested first was randomized in each subject, followed immediately by single-leg hops. Finally, the same pre-exhaustion exercise protocol was repeated at 50% of 1 RM for the contralateral leg. Each subject’s knee flexing and knee extending cadence was not fixed during the knee-extension exercise. Instead, each subject was allowed to establish a “groove”, i.e. use a self-selected cadence. The best hop performance (that is, the hop with maximal hop distance) for each test conditions was recorded.

The same investigator supervised the tests for all subjects. Verbal encouragement and instructions were standardised. Before both the pre-test and testing sessions, each subject performed a warm-up consisting of five minutes of ergometer cycling at 70 r.p.m. at a submaximal work level, followed by 20 repetitions of bilateral standing toe raises.

For the second experiment, a biomechanical analysis of maximal single-leg hops during fatigued and nonfatigued conditions was performed using the same test protocol as for the first experiment. A three-dimensional motion analysis system (Qualisys Medical AB, Göteborg, Sweden) that consisted of six cameras, passive reflective markers and a computer running a software package (Qtrac Capture-Version 2.57, Adaptive Optics Associates, Inc., Cambridge, MA, U.S.A) was used for the acquisition of kinematic data. Kinetic data were collected with a Kistler force plate (Kistler 9281C, Kistler Instrumente AG, Winterthur, Switzerland). Kinematic and kinetic data were recorded at 240 Hz. The camera system was calibrated to a measurable volume of 13.8 m³ (3 x 2 x 2.3 m). The passive reflective markers were attached directly to the skin (and shoes) of each subject to minimize errors between the markers and the actual joint centers, according to the set-up of Fig. 1. The data for the kinematic coordinates, ground-reaction forces, and moments and powers were imported into customized software to compute joint kinematics, segmental inertia properties, and joint kinetics using an inverse dynamics model. The variables that were evaluated included the range of motion, moments and powers of the three lower-extremity joints, together with ground-reaction forces, i.e. horizontal force (Fx),
medio-lateral force ($F_y$), vertical force ($F_z$) and the resultant vector of vertical and horizontal forces ($F_{zx}$). The joint kinetic values were normalised to the body mass for each subject. By convention, both the positive and the negative values for joint movement would represent extensor and flexor moment, and positive and negative power values would indicate energy generation and absorption. During take-off, hip, knee and ankle angles values were documented, when the right anterior spina iliac superior-marker was at its deepest position. During landing, hip, knee and ankle angles values were
collected at peak vertical ground-reaction force. The subjects hopped either from the force platform or to the force platform for all test conditions. To study fatigue recovery following the pre-exhaustion exercise protocol, the subjects again performed single-leg hops after a recovery period of three minutes.

Statistical Methods

For the first experiment, the intraclass correlation (ICC) coefficient was evaluated for the analysis of test-retest reliability under different hop test conditions, according to Shrout & Fleiss (1979). The Friedman test was used to determine differences in hop performance between fatigued and nonfatigued hop test conditions. Differences between the number of hop trials and knee-extension repetitions performed at test and retest were computed using the Wilcoxon signed-rank test. For the second experiment, comparisons between the biomechanical variables that were obtained were made with the Friedman test. Significance was considered at the $\alpha$ level of $P<0.05$. 
Results

Test-retest reliability for different hop test conditions

For the first experiment, we found high ICC values when analysing test-retest reliability of hop performance (measured as maximal hop length) during the different test conditions (Fleiss 1986). ICCs were 0.75, 0.91 and 0.98, respectively, for the 50% quadriceps strength-hop condition, the 80% quadriceps strength-hop condition, and the nonfatigued-hop condition. The mean number (±SD) of hop trials needed to obtain three successful hops at test and retest under nonfatigued test conditions was 3.5 (range 3-5) and 3.3 (range 3-5), with no significant differences between tests. The number of hop trials following pre-exhaustion exercise of the quadriceps muscle at 50% of 1 RM was 4.5 (range 3-6) and 3.5 (3-5), with a significant (P<0.05) difference between test and retest. Following pre-exhaustion exercise of the quadriceps muscle at 80% of 1 RM, the number of hop trials was 3.8 (range 3-6) and 3.3 (range 3-5), with no significant differences between tests. The average number (±SD) of knee-extension repetitions at 50% of 1 RM was 16.7±2.4 and 17.3±2.7, with no significant differences between test and retest. The mean number (±SD) of knee-extension repetitions at 80% of 1 RM was 7.1±1.5 and 8.0±1.3, with a significant (P<0.05) difference between test and retest.

Hop performance under different test conditions

Hop performance decreased significantly, 29 cm (20%) and 16 cm (11%), respectively, following pre-exhaustion exercise of the quadriceps muscle at 50% and 80% of 1 RM, compared with the nonfatigued test condition (P<0.01). Moreover, hop performance decreased significantly, 13 cm (9%), following pre-exhaustion exercise of the quadriceps muscle at 50% compared with 80% of 1 RM (P<0.01) (Table 1).

Joint range of motion

For the second biomechanical experiment, significant (P<0.05) decreases were observed for hip and knee flexion angles for the fatigued hop conditions compared with the nonfatigued hop condition during the ground contact portion of the take-off (defined as the right anterior spina iliacc medialis-marker being at its deepest position) (Table 2 and 3). A graph for hip, knee and ankle joint angles, moments and powers, as well as ground-reaction forces, during the take-off for a representative subject is shown in Fig. 2. During landing, hip, knee and ankle angles values were collected at peak vertical ground-reaction forces. No significant differences were found during landing between joint flexion angles for the nonfatigued hop test condition compared with the 50% quadriceps strength-hop condition (Table 4). Significant (P<0.01) differences were found during landing between the nonfatigued hop test condition and the 80% quadriceps strength-hop test condition for hip flexion angles (Table 5).
Fig. 2. Representative hip, knee and ankle joint angles, moments and powers, as well as ground-reaction forces during the take-off for a single subject for nonfatigued and fatigued (50% of quadriceps muscle 1 RM-strength) hop conditions. The vertical dotted lines indicate the time of take-off when the subject becomes airborne.
Kinetics

As seen in Table 2, during the take-off for the single-leg hops, moments for the knee and ankle joints, and generated powers for the hip, knee and ankle joints decreased for the 50% quadriceps strength-hop condition compared with the nonfatigued hop condition \((P<0.05)\). Significant differences for hip joint moment and knee and ankle joint powers were found between the nonfatigued hop test condition and the 80% quadriceps strength-hop test condition \((P<0.05)\) (Table 3). The hip, knee and ankle joint powers generated during the take-off differed significantly for different hop conditions \((P<0.05)\). The percentage contributions at the hip, knee and ankle joints to the total generated powers generated by all three joints for different hop conditions were 28% to 36% (7.0 to 10.4 W/kg body mass), 20% to 31% (3.9 to 11.6 W/kg body mass) and 41% to 44% (8.5 to 15.0 W/kg body mass), respectively (Fig. 3). Compared with landing during the nonfatigued condition, hip moment and absorbed knee power were lower for the 50% quadriceps strength-hop condition \((P<0.05)\) (Table 4), whereas hip moment decreased for the 80% quadriceps strength-hop condition \((P<0.01)\) (Table 5). The mean absorbed power values were typically two to three times higher for the knee than for the hip and five to ten times higher for the knee than for the ankle during landing for all test conditions \((P<0.01)\) (Fig. 4).

![Fig. 3.](image-url)

**Fig. 3.** Comparison of generated power values during the take-off for the hip, knee and ankle joint for different hop test conditions. Values are expressed as means \((±SD)\). *\(P<0.05\). **\(P<0.01\). ***\(P<0.001\).
Ground-reaction forces

During the take-off for the single-leg hops, the horizontal forces decreased for the 50% quadriceps strength-hop condition compared with the nonfatigued hop condition (Table 2), whereas the vertical and horizontal forces, as well as the resultant vector of vertical and horizontal forces, decreased for the 80% quadriceps strength-hop condition (Table 3) \((P<0.05)\). Compared with landing during the nonfatigued condition, the vertical and horizontal forces, as well as the resultant vector of vertical and horizontal forces, decreased following pre-exhaustion of the quadriceps muscle at 50% of 1 RM-strength (Table 4), whereas the vertical forces and the resultant vector of vertical and horizontal forces decreased following pre-exhaustion of the quadriceps muscle at 80% of 1 RM-strength (Table 5) \((P<0.05)\). There was no significant difference in medio-lateral force between hop test conditions at take-off or during landing (Tables 2-5).

**Fig. 4.** Comparison of absorbed power values during landings for the hip, knee and ankle joint for different hop test conditions. Values are expressed as means \((±SD)\). **\(P<0.01\). ***\(P<0.001\).
Recovery

Almost all the measured variables had fully recovered three minutes post-exercise for the fatigued hop conditions (i.e. following pre-exhaustion of the quadriceps muscle at 80% and 50% of 1 RM-strength) during take-offs and landings (Tables 2-5). However, after three minutes of recovery there was a decrease in knee flexion angles at the take-off for the 80% quadriceps strength-hop condition ($P<0.05$) (Table 3). Moreover, the horizontal force at landing was significantly lower for the 50% quadriceps strength-hop condition protocol following recovery ($P<0.05$) (Table 4).

Table 1. Hop performance for test and retest under different test conditions in healthy male subjects ($n=11$). Values are expressed as means ($\pm$SD).

<table>
<thead>
<tr>
<th>Quadriceps muscle 1 RM-strength (%)</th>
<th>Nonfatigued</th>
<th>80</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hop performance (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>169.4±20.4**¤</td>
<td>152.6±20.2*</td>
<td>139.5±12.2</td>
</tr>
<tr>
<td>Retest</td>
<td>168.8±20.2**¤¤</td>
<td>153.0±20.4**</td>
<td>141.3±22.5</td>
</tr>
</tbody>
</table>

¤ Different from 80% quadriceps strength-hop condition, $P<0.01$.
¤¤ Different from 80% quadriceps strength-hop condition, $P<0.001$.
* Different from 50% quadriceps strength-hop condition, $P<0.01$.
** Different from 50% quadriceps strength-hop condition, $P<0.001$. 
Table 2. Hip, knee and ankle joint angles, moments and powers and ground-reaction forces during the take-off for the nonfatigued hop test condition, the 50% quadriceps strength-hop test condition and the recovered hop test condition, respectively. Values are expressed as means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>Flexion Angles (°)</th>
<th>Moment (Nm/kg)</th>
<th>Generated Power (W/kg)</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nonfatigued</td>
<td>50% strength</td>
<td>Recovery (3 min)</td>
<td></td>
</tr>
<tr>
<td>Flexion Angles (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>79.79 ± 7.96**</td>
<td>58.26 ± 7.28</td>
<td>77.47 ± 5.64**</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>66.56 ± 8.55**</td>
<td>54.78 ± 5.98</td>
<td>61.34 ± 9.21**</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>31.11 ± 4.75</td>
<td>27.44 ± 3.40</td>
<td>30.84 ± 3.90</td>
<td></td>
</tr>
<tr>
<td>Moment (Nm/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>4.11 ± 1.58</td>
<td>2.95 ± 0.42</td>
<td>3.44 ± 0.68</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>2.25 ± 0.98**</td>
<td>1.49 ± 0.44</td>
<td>1.96 ± 0.70**</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>2.44 ± 0.18**</td>
<td>2.22 ± 0.20</td>
<td>2.55 ± 0.17**</td>
<td></td>
</tr>
<tr>
<td>Generated Power (W/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>10.29 ± 2.89*</td>
<td>7.04 ± 0.74</td>
<td>10.47 ± 3.23</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>10.24 ± 4.67**</td>
<td>3.93 ± 0.85</td>
<td>7.84 ± 3.17**</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>14.58 ± 2.23**</td>
<td>8.53 ± 1.49</td>
<td>13.28 ± 1.86**</td>
<td></td>
</tr>
<tr>
<td>Force (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fx</td>
<td>587.54 ± 110.22**</td>
<td>373.36 ± 72.77</td>
<td>543.68 ± 90.64**</td>
<td></td>
</tr>
<tr>
<td>Fy</td>
<td>60.36 ± 15.09</td>
<td>65.66 ± 22.33</td>
<td>57.93 ± 16.55</td>
<td></td>
</tr>
<tr>
<td>Fz</td>
<td>1441.60 ± 172.81</td>
<td>1355.61 ± 170.49</td>
<td>1470.85 ± 211.96*</td>
<td></td>
</tr>
<tr>
<td>Fzx</td>
<td>1557.53 ± 197.21</td>
<td>1407.44 ± 172.02</td>
<td>1568.49 ± 227.31</td>
<td></td>
</tr>
</tbody>
</table>

*Difference (P<0.05) from 50% quadriceps strength-hop condition.
**Difference (P<0.01) from 50% quadriceps strength-hop condition.

Table 3. Hip, knee and ankle joint angles, moments and powers and ground-reaction forces during the take-off for the nonfatigued hop test condition, the 80% quadriceps strength-hop test condition and the recovered hop test condition, respectively. Values are expressed as means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>Flexion Angles (°)</th>
<th>Moment (Nm/kg)</th>
<th>Generated Power (W/kg)</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nonfatigued</td>
<td>80% strength</td>
<td>Recovery (3 min)</td>
<td></td>
</tr>
<tr>
<td>Flexion Angles (°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>78.64 ± 12.32*</td>
<td>66.18 ± 13.58</td>
<td>69.81 ± 20.52</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>63.55 ± 5.53**¤</td>
<td>56.79 ± 7.02</td>
<td>57.88 ± 9.04</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>27.42 ± 4.68</td>
<td>27.66 ± 2.84</td>
<td>28.60 ± 6.30</td>
<td></td>
</tr>
<tr>
<td>Moment (Nm/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>4.31 ± 1.32*</td>
<td>3.39 ± 0.59</td>
<td>3.60 ± 0.79</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>2.43 ± 0.87</td>
<td>1.76 ± 0.56</td>
<td>1.94 ± 0.37</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>2.51 ± 0.25</td>
<td>2.48 ± 0.20</td>
<td>2.66 ± 0.36*</td>
<td></td>
</tr>
<tr>
<td>Generated Power (W/kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>10.39 ± 1.02</td>
<td>8.93 ± 2.20</td>
<td>10.15 ± 2.44</td>
<td></td>
</tr>
<tr>
<td>Knee</td>
<td>11.58 ± 4.00*</td>
<td>6.19 ± 2.54</td>
<td>8.57 ± 2.92</td>
<td></td>
</tr>
<tr>
<td>Ankle</td>
<td>15.03 ± 2.15**</td>
<td>11.80 ± 2.61</td>
<td>15.44 ± 3.88**</td>
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</tr>
<tr>
<td>Force (N)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fx</td>
<td>579.08 ± 117.40**</td>
<td>419.55 ± 63.65</td>
<td>525.07 ± 57.91**</td>
<td></td>
</tr>
<tr>
<td>Fy</td>
<td>72.74 ± 15.29</td>
<td>65.67 ± 19.83</td>
<td>70.83 ± 23.42</td>
<td></td>
</tr>
<tr>
<td>Fz</td>
<td>1555.93 ± 238.50*</td>
<td>1411.94 ± 231.69</td>
<td>1542.54 ± 198.12</td>
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</tr>
<tr>
<td>Fzx</td>
<td>1661.84 ± 252.69**</td>
<td>1473.65 ± 235.12</td>
<td>1629.68 ± 204.18**</td>
<td></td>
</tr>
</tbody>
</table>

*Difference (P<0.05) from 80% quadriceps strength-hop condition.
**Difference (P<0.01) from 80% quadriceps strength-hop condition.
¤Difference (P<0.01) from recovered-hop condition.
### Table 4. Hip, knee and ankle joint angles, moments and powers and ground-reaction forces during landing for the nonfatigued hop test condition, the 50% quadriceps strength-hop test condition and the recovered hop test condition, respectively. Values are expressed as means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>Nonfatigued</th>
<th>50% strength</th>
<th>Recovery (3 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexion Angles (°)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>61.67 ± 6.38</td>
<td>51.51 ± 11.60</td>
<td>60.74 ± 6.02</td>
</tr>
<tr>
<td>Knee</td>
<td>21.97 ± 5.35</td>
<td>19.44 ± 6.44</td>
<td>21.87 ± 3.71</td>
</tr>
<tr>
<td>Ankle</td>
<td>-1.90 ± 6.29</td>
<td>-4.54 ± 3.05</td>
<td>-7.49 ± 6.87</td>
</tr>
<tr>
<td><strong>Moment (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>14.44 ± 4.13*</td>
<td>6.27 ± 2.71</td>
<td>11.67 ± 3.02</td>
</tr>
<tr>
<td>Knee</td>
<td>3.00 ± 4.82</td>
<td>-1.61 ± 0.82</td>
<td>-3.18 ± 3.81</td>
</tr>
<tr>
<td>Ankle</td>
<td>1.02 ± 2.11</td>
<td>-0.42 ± 0.27</td>
<td>0.88 ± 2.06</td>
</tr>
<tr>
<td><strong>Absorbed Power (W/kg)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>-11.13 ± 3.54</td>
<td>-10.66 ± 5.12</td>
<td>-11.22 ± 6.63</td>
</tr>
<tr>
<td>Knee</td>
<td>-29.79 ± 5.09**</td>
<td>-18.80 ± 2.99</td>
<td>-25.98 ± 5.60**</td>
</tr>
<tr>
<td>Ankle</td>
<td>-2.43 ± 3.97</td>
<td>-4.06 ± 0.58</td>
<td>-4.49 ± 2.14</td>
</tr>
<tr>
<td><strong>Force (N)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fx</td>
<td>-1679.88 ± 318.86*¤</td>
<td>-1048.47 ± 302.71</td>
<td>-1339.91 ± 219.10*</td>
</tr>
<tr>
<td>Fy</td>
<td>-250.78 ± 202.46</td>
<td>-174.49 ± 45.60</td>
<td>-262.75 ± 131.33</td>
</tr>
<tr>
<td>Fz</td>
<td>3729.10 ± 882.09**</td>
<td>2491.83 ± 418.55</td>
<td>3371.24 ± 550.88**</td>
</tr>
<tr>
<td>Fzx</td>
<td>4095.32 ± 908.10**</td>
<td>2709.25 ± 476.92</td>
<td>3643.46 ± 456.99**</td>
</tr>
</tbody>
</table>

¤Difference (P<0.05) from recovered hop condition.  
*Difference (P<0.05) from 50% quadriceps strength-hop condition.  
**Difference (P<0.01) from 50% quadriceps strength-hop condition.

### Table 5. Hip, knee and ankle joint angles, moments and powers and ground-reaction forces during landing for the nonfatigued hop test condition, the 80% quadriceps strength-hop test condition and the recovered hop test condition, respectively. Values are expressed as means (±SD).

<table>
<thead>
<tr>
<th></th>
<th>Nonfatigued</th>
<th>80% strength</th>
<th>Recovery (3 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flexion Angles (°)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>58.19 ± 12.18**</td>
<td>48.30 ± 5.84</td>
<td>58.55 ± 10.40**</td>
</tr>
<tr>
<td>Knee</td>
<td>21.61 ± 2.40</td>
<td>17.18 ± 3.77</td>
<td>18.73 ± 7.27</td>
</tr>
<tr>
<td>Ankle</td>
<td>-5.54 ± 7.78</td>
<td>-4.44 ± 4.74</td>
<td>-5.10 ± 6.35</td>
</tr>
<tr>
<td><strong>Moment (Nm/kg)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>13.47 ± 5.65**</td>
<td>7.75 ± 2.84</td>
<td>12.96 ± 7.83**</td>
</tr>
<tr>
<td>Knee</td>
<td>-2.86 ± 5.01</td>
<td>-2.37 ± 1.06</td>
<td>-3.10 ± 6.23</td>
</tr>
<tr>
<td>Ankle</td>
<td>-0.14 ± 1.12</td>
<td>-0.02 ± 0.82</td>
<td>-0.51 ± 1.13</td>
</tr>
<tr>
<td><strong>Absorbed Power (W/kg)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hip</td>
<td>-9.52 ± 1.75</td>
<td>-10.07 ± 6.34</td>
<td>-8.75 ± 3.86</td>
</tr>
<tr>
<td>Knee</td>
<td>-31.11 ± 7.88</td>
<td>-22.97 ± 7.53</td>
<td>-22.12 ± 4.14</td>
</tr>
<tr>
<td>Ankle</td>
<td>-4.79 ± 4.35</td>
<td>-5.46 ± 1.48</td>
<td>-4.91 ± 3.73</td>
</tr>
<tr>
<td><strong>Force (N)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fx</td>
<td>-1628.42 ± 420.48</td>
<td>-1238.85 ± 226.34</td>
<td>-1751.56 ± 439.10*</td>
</tr>
<tr>
<td>Fy</td>
<td>-171.31 ± 359.16</td>
<td>-237.42 ± 115.03</td>
<td>-272.89 ± 124.96</td>
</tr>
<tr>
<td>Fz</td>
<td>3260.52 ± 729.12*</td>
<td>2777.54 ± 509.15</td>
<td>3438.57 ± 779.30</td>
</tr>
<tr>
<td>Fzx</td>
<td>3651.02 ± 805.81**</td>
<td>3046.68 ± 520.68</td>
<td>3861.49 ± 880.88**</td>
</tr>
</tbody>
</table>

*Difference (P<0.05) from 80% quadriceps strength-hop condition.  
**Difference (P<0.01) from 80% quadriceps strength-hop condition.
Discussion

The aim of our study was firstly to develop, and to examine the reliability of, a single-leg hop test performed under standardised, fatigued conditions using pre-exhaustion exercise, and secondly, to obtain biomechanical information about the effect of quadriceps muscle fatigue on the kinetic and kinematic behaviour of the lower-extremity during single-leg hops. For the first experiment, the test-retest reliability of different hop test conditions was determined. Hop performance under all three test conditions was found to have high test-retest reliability. We have thus developed a reliable method that is easy to perform and record and which, in the clinical setting, can be used to compare functional performance under different, standardised test conditions. For the second biomechanical experiment, the main findings were that hip and knee flexion angles, knee and ankle joint power, and ground-reaction forces decreased for the fatigued hop conditions compared with the nonfatigued condition during the take-off for the single-leg hops. Compared with landing during the nonfatigued condition, hip moments and ground-reaction forces were lower for the fatigued hop conditions. The absorbed power values were two to three times greater for the knee than for the hip and five to ten times greater for the knee than for the ankle during landing for all test conditions. Most measured variables had recovered three minutes post-exercise.

Two aspects of the test-retest results deserve mentioning; firstly, the fact that the test-retest reliability decreased as fatigue of the quadriceps muscle increased (from 0.98 to 0.75) indicates that a pre-exhaustion exercise protocol generating more than 50% muscle fatigue may lead to poorer reproducibility. It is not unexpected that reproducibility decreases when the level of muscle fatigue increases. For example, Johnston et al. (1998) found significant decreases in motor control performance following lower-extremity exercise to fatigue. Our results at 50% quadriceps muscle strength are in agreement with those reported by Pincivero, Lephart, Karunakara (1997b), who obtained test-retest ICC values ranging from 0.52 to 0.74 for a muscular endurance test of 30 maximal repetitions of isokinetic knee extension/flexion at 180°/s. Moreover, Manske, Smith, Wyatt (2003) recently investigated whether multijoint isokinetic testing before functional testing altered test-retest reliability of several functional tests (including the single-leg hop) of the lower-extremity. It was found that test-retest reliability was high for all functional tests, with ICCs ranging from 0.91 to 0.98 (ICC value for the single-leg hop test was 0.96). Secondly, in our study, the average number of knee-extension repetitions differed significantly ($P<0.05$) between test (7.1 repetitions) and retest (8.0 repetitions) at 80% of 1 RM. This difference may be the result of a learning process, as well as feedback in the form of knowledge of results from the previous test session. However, although there was a difference in the number of knee-extension repetitions performed by subjects at 80% of 1 RM, the hop test-retest reliability was high (ICC value
The fatigue induced by our pre-exhaustion exercise protocol was probably the result of peripheral fatigue, i.e. changes within the quadriceps muscle itself, rather than a failure of central drive. This is supported by James, Sacco, Jones (1995), who demonstrated a minimal reduction in central drive during heavy exercise, resulting in a 50% loss of power. Furthermore, Beelen, Sargeant, Jones, de Ruiter (1995) noted a close association between the changes in electrically elicited force and voluntary force following high-intensity dynamic exercise. The authors (Beelen et al., 1995) suggest that fatigue may be due to changes in the contractile apparatus and is probably not a result of reduced muscle activation by the central nervous system. Peripheral fatigue can be further divided into high- and low-frequency fatigue (Edwards, Hill, Jones, Merton, 1977). High-frequency fatigue occurs as a result of an impairment in action potential propagation over the sarcolemma; low-frequency fatigue denotes an impairment in excitation-contraction coupling. During high intensity exercise of short duration, as in our study, high frequency fatigue has been suggested as the dominant reason for the loss of force-generating capability (Strojnik & Komi, 1998).

The movement velocity during the exhaustive knee-extension exercise set was not controlled in our study. This is due to the fact that the cadence consistently decreases from the first to the last repetition for a subject during a set of heavy weight training exercise (Jones, Hunter, Fleisig, Escamilla, Lemak, 1999).

When it came to the biomechanical experiment, the hip and knee joints responded with a reduction in flexion angles during the take-off for the fatigued conditions, i.e. subjects used a more erect body position. This probably resulted in the subjects being less capable of generating horizontal forces for the fatigued conditions. During landing, no significant changes in joint flexion angles were seen, except for the hip joint, which was more extended for the 80% quadriceps strength condition. Similarly, Decker, Torry, Noonan, Riviere, Sterett (2002), who investigated landing performance during a 60-cm vertical drop landing by subjects with anterior cruciate ligament (ACL) reconstruction, reported a greater hip extension at initial ground contact compared with healthy subjects. Thus, an extension of the hip seems to be an adaptation made by subjects with knee injury, or during conditions of quadriceps fatigue in healthy subjects, during high-demand landings.

During the take-off for the single-leg hops, moments and generated powers for the hip, knee and ankle joints decreased for the fatigued conditions. The decrease in joint moment during fatigued hop conditions ranged from 9% to 44%, whereas the reduction in power ranged from 16% to 62%, indicating that when fatigued, subjects were typically less capable of generating power than moment. This is in accordance with the observation by Alkjaer, Simonsen,
Magnusson, Aagaard, Dyhre-Poulsen (2002), that power of the knee extensors during a forward lunge was significantly lower in ACL deficient subjects than in healthy controls. Presumably, the difference in power for the ACL deficient subjects was primarily due to a slower angular velocity in the flexion part and to both reduced moment and slower angular velocity during the extension part.

Our findings showed that the quadriceps muscle contributed significantly for the propulsive phase of single-leg hops (Fig. 3). In contrast, Robertson & Fleming (1987) estimated that the contributions by the hip, knee and ankle extensor muscles were as follows: 46%, 4%, and 50%, respectively, during standing broad (horizontal) jumping. The results of our study, however, demonstrate that strong quadriceps muscles are necessary for optimal hop for distance performance.

Single-leg hop tests are often used as predictors of dynamic knee joint function, particularly in subjects with ACL injury (Fitzgerald, Lephart, Hwang, Wainner, 2001). For example, a ratio of limb symmetry known as the limb symmetry index (LSI) has been the most frequently reported criterion for assessing whether a hop test is normal or abnormal (Ageberg, 2002). The LSI is used to calculate the difference in hop length — i.e. the ability to generate power at the take-off — between the injured and uninjured sides. To our knowledge, however, no previous studies have investigated the magnitude of eccentric loading on the knee joint during single-leg hop landings; a situation which could be considered highly demanding on knee function. We noted that absorbed power values were two to three times greater for the knee than for the hip, and five to ten times greater for the knee than for the ankle during landing for all test conditions (Fig. 4). Based on our results, it is possible that, during single-leg hop tests, for clinical or scientific purposes, the focus of interest should shift from the ability to generate power during the take-off to the ability to absorb power during landing. Thus, we suggest that in order to obtain a more comprehensive assessment of knee function (e.g. after ACL injury), attention should not centre exclusively on comparisons between the hop distance on the injured and uninjured sides, but also on the ability to successfully perform landings.

During the take-off for the single-leg hops, the horizontal ground-reaction forces decreased significantly for the fatigued conditions. As mentioned earlier, this is probably due to the fact that the hip and knee joints responded with a decrease in flexion angles during the take-off for the fatigued conditions, i.e. subjects used a more erect body position. Moreover, the single-leg hop distance decreased significantly as a result of quadriceps muscle fatigue (Table 1). For this reason, the vertical and horizontal ground-reaction forces during landing were probably lower for the fatigued conditions because a reduction in hop length also results in a decrease of impact forces. This is in accordance with Zhang et al. (2000), who investigated changes in lower-extremity energy
absorption for drop jumps of different heights. It was demonstrated, that with increases in jump height, there were increases in ground-reaction forces.

Most measured variables had fully recovered three minutes post-exercise for the fatigued hop conditions during both take-off and landing. Schwender, Mikesky, Wigglesworth, Burr (1995) evaluated subjects for fatigue and recovery following fatiguing isokinetic exercise of the quadriceps muscle. It was found that recovery varied among subjects, but was directly related to the decline in force output. In our study, there was a difference in the decline in force output for the two fatigue protocols, as quadriceps muscle performance fell to 50% and 80% of 1 RM-strength, respectively. However, recovery of the measured variables of hop performance following the different fatigue protocols was similar three minutes post-exercise.

**Perspective**
Although injuries tend to occur more frequently at the end of a sporting event, when a participant is fatigued (Dugan & Frontera 2000; Feagin et al. 1987; Östenberg & Roos 2000), tests of functional performance for sports or rehabilitation purposes are typically performed under nonfatigued test conditions. Therefore, our pre-exhaustion exercise protocol combined with single-leg hop testing may improve the possibilities to evaluate the effects of training or rehabilitation interventions, as it affords examination of lower-extremity muscle function under conditions of fatigue. The large negative power values observed at the knee joint during the landing phase of the single-leg hop, during which the quadriceps muscle activates eccentrically, indicate that not only hop distance but also the ability to perform successful landings should be investigated when assessing dynamic knee function. However, more research is needed and a challenge for future research should be to compare the dynamic performance of the healthy and injured leg under different test conditions during rehabilitation and follow-up in patients with ACL injury or reconstruction, for a more comprehensive assessment of lower-extremity function.

**Acknowledgements**
This study was supported by a grant from the Swedish National Centre for Research in Sports.
References


Study V
Introduction

Injuries often tend to occur at the end of a sporting event, when a participant is fatigued [10, 12, 35]. However, it has been our observation that current functional tests, such as the single-leg hop, are typically performed under non-fatigued test conditions both in the clinical and scientific setting. The ability of these tests to assess whether a patient has regained lower-extremity function after anterior cruciate ligament (ACL) reconstruction, for example, could therefore be regarded as limited. In accordance with this, the reported sensitivity of several types of hop tests in detecting functional limitations in ACL-deficient knees was relatively low [23, 29]. To improve the sensitivity of tests of lower-extremity function in evaluating the effect of rehabilitation interventions, the testing of dynamic function under fatigued conditions has been suggested [6]. We have previously developed, and examined the reliability of a single-leg hop test performed under standardised, fatigued conditions in healthy subjects. The results of this work showed high test-retest reliability for the fatigued hop-test condition (J. Augustsson et al., submitted). We hypothesised that performing single-leg hop testing under conditions of fatigue may be more sensitive in detecting functional impairment after ACL reconstruc-

Abstract  The aim of this study was to investigate the ability of a new hop test to determine functional deficits after anterior cruciate ligament (ACL) reconstruction. The test consists of a pre-exhaustion exercise protocol combined with a single-leg hop. Nineteen male patients with ACL reconstruction (mean time after operation 11 months) who exhibited normal single-leg hop symmetry values (≥90% compared with the non-involved extremity) were tested for one-repetition maximum (1 RM) strength of a knee-extension exercise. The patients then performed single-leg hops following a standardised pre-exhaustion exercise protocol, which consisted of unilateral weight machine knee-extensions until failure at 50% of 1 RM. Although no patients displayed abnormal hop symmetry when non-fatigued, 68% of the patients showed abnormal hop symmetry for the fatigued test condition. Sixty-three per cent exhibited 1 RM strength scores of below 90% of the non-involved leg. Eighty-four percent of the patients exhibited abnormal symmetry in at least one of the tests. Our findings indicate that patients are not fully rehabilitated 11 months after ACL reconstruction. It is concluded that the pre-exhaustion exercise protocol, combined with the single-leg hop test, improved testing sensitivity when evaluating lower-extremity function after ACL reconstruction. For a more comprehensive evaluation of lower-extremity function after ACL reconstruction, it is therefore suggested that functional testing should be performed both under non-fatigued and fatigued test conditions.

Keywords  Anterior cruciate ligament · Knee · Rehabilitation · Muscle fatigue · Exercise test
tion, when compared with traditional, non-fatigued hop testing.

The purpose of this study was to investigate the ability of a new hop test to determine functional deficits after ACL reconstruction.

Materials and methods

Patients

Nineteen male patients with a unilateral ACL injury who had undergone ACL reconstruction were recruited for this study in a consecutive manner from a cohort of patients that had undergone reconstruction of the ACL at Sahlgrenska University Hospital, Östra, Sweden. The inclusion criteria included there being no other or subsequent injuries to the surgical limb, and no injury to the uninvolved knee, hips, ankles or back. Further inclusion criteria were at least six months of post-operative physical therapy, a single-leg hop symmetry index of ≥90%, age between 20 and 35 years, male gender and pain intensity of less than five on a 10-cm visual analogue scale (VAS) on the day of the examination. Clinical knee-joint examination, performed on both of the patients' knees by an experienced physical therapist (R.T.), revealed no signs of increased laxity (using the Lachman test), swelling, joint line tenderness or decreased range of motion.

The descriptive data of the patients was mean (±SD) age, body weight and height of 28±5 years, 79±8 kg and 182±5 cm respectively. Mean (±SD) time since surgery was 11±2 months, whereas the mean time (±SD) between the index injury and reconstruction was 22±17 months. All the patients were at least recreational athletes and 69% (13/19) had returned to their previous level of sports participation. In 16 cases, the ruptured ACL was reconstructed with a patellar tendon autograft, whereas a hamstring-tendon autograft was used in three cases. In ten cases, the right leg was the injured leg, whilst in nine cases the left leg was the injured leg. Eleven patients had an isolated rupture of the ACL, seven patients had ruptures of the lateral meniscus and one patient had a rupture of the medial meniscus. The study was approved by the Human Ethics Committee at the Faculty of Medicine, Göteborg University, Sweden. Informed written consent was obtained and the rights of patients were protected.

Research design

Each patient performed three testing sessions, with at least 7 days between sessions. At the first session, a hop test under non-fatigued conditions was performed for familiarisation purposes and in addition knee-extension one-repetition maximum (1 RM) strength was determined. At the second session, knee-extension 1 RM strength was determined again in a test-retest design. The hop test was then performed under fatigued conditions (see below for test procedure) for familiarisation purposes. At the third session, patients performed the hop test under non-fatigued and fatigued test conditions.

All the strength and functional tests were conducted in a blinded fashion, as patients concealed their knees by wearing elastic wraps. In this way, the test leader (J.A.) did not know whether the involved or the non-involved leg was being tested during a particular test session.

Pre-test procedures

When performing the single-leg hop test, the patient was instructed to stand on one leg and to position his toes to a mark on the floor. The patient was then instructed to hop forward as far as possible and to land on the same leg. The patient was instructed to hold his hands on his hips throughout the jump. The distance, in centimetres, was measured from the toe in the starting position to the heel where the patient landed. A hop was only regarded as successful if the patient was able to keep his foot in place after landing (i.e., no extra hops for balance correction were allowed) until the investigator had marked where the patient landed. The test was performed until three successful hops were made with each leg, with the starting order of the right or the left leg randomly assigned to the patients. For the non-fatigued condition, each patient was given two practice trials before the test.

Each patient’s unilateral 1 RM for the involved and the uninvolved leg was determined for a knee-extension exercise by using the maximum weight that could be lifted for one repetition. Patients were placed in a variable-resistance knee-extension machine (Model Leg Extension FL 130, Competition Line, Borås, Sweden). Each patient was instructed in the proper technique for the exercise by the test leader. The patients performed two sub-maximal warm-up sets of the knee-extension exercise. The starting and ending positions for the knee-extension exercise were seated with a knee flexion angle of approximately 90°. From the starting position, each patient extended his knee and returned to the starting position. The pad supporting the leg was adjusted so that the axis of the knee joint was aligned with the axis of the resistance arm. The foot was positioned approximately 5 cm proximal to the lateral malleolus. The weight lifted for each trial was incremented by 2.5–10 kg until failure occurred. One minute of rest was allowed between trials. The starting order of the right or the left leg was randomly assigned to patients.

A strength [26] and hop [19] symmetry index of ≥90% (involved versus non-involved side) was considered to be within normal ranges.
The hop performance was compared in two standardised test conditions: (1) non-fatigued, and (2) immediately following pre-exhaustion exercise of the quadriceps muscle at 50% of 1 RM strength (Fig. 1). In order to standardise the fatiguing exercise, we used a fatigue protocol developed from previous work on healthy subjects [5], (J. Augustsson et al., submitted). This fatigue protocol consists of a so-called “pre-exhaustion exercise”, which involves working a muscle to fatigue by performing as many repetitions as possible in a single set at a load of, for example, 50% of 1 RM, using a single-joint exercise; this exercise is immediately followed by a multijoint exercise. By adopting the concept of pre-exhaustion exercise, and by using the RM continuum, we have constructed a testing protocol that quantifies both the level and the progression of muscle fatigue.

Specifically, a “target force” of pre-exhaustion activations can be set at a given percentage of 1 RM strength (for example, 50% of 1 RM) and in turn allow for any degree of muscle fatigue to be obtained in a controlled manner. So, if a subject performs as many repetitions as possible of a knee-extension exercise until failure at 50% of 1 RM, for example, quadriceps 1 RM strength is consequently reduced by 50%.

Each patient began testing by performing single-leg hops for the involved and uninvolved limb under non-fatigued conditions, as previously described. The patients then performed unilateral fatiguing knee-extensions until failure occurred at 50% of their respective 1 RM, using a variable-resistance knee-extension machine, followed immediately by single-leg hops. The leg tested first was randomised in each patient.

Each patient’s knee-flexing and knee-extending cadence was not fixed during the knee-extension exercise; instead, each patient was allowed to establish a “groove”, i.e. use a self-selected cadence. The best hop performance for the two test conditions was recorded. The number of hop trials needed to make three successful hops for the different test conditions was documented, as well as the number of knee-extension repetitions performed at 50% of 1 RM.

Verbal encouragement and instructions were standardised. Before both the pre-test and the testing sessions, each patient performed a warm-up consisting of 10 min of ergometer cycling at 70 rpm at a sub-maximal work level, followed by 15 squats and 20 repetitions of toe raises. All the patients wore the same type of athletic shoes during all the sessions.

Experimental protocol

The hop performance was compared in two standardised test conditions: (1) non-fatigued, and (2) immediately following pre-exhaustion exercise of the quadriceps muscle at 50% of 1 RM strength (Fig. 1). In order to standardise the fatiguing exercise, we used a fatigue protocol developed from previous work on healthy subjects [5], (J. Augustsson et al., submitted). This fatigue protocol consists of a so-called “pre-exhaustion exercise”, which involves working a muscle to fatigue by performing as many repetitions as possible in a single set at a load of, for example, 50% of 1 RM, using a single-joint exercise; this exercise is immediately followed by a multijoint exercise. By adopting the concept of pre-exhaustion exercise, and by using the RM continuum, we have constructed a testing protocol that quantifies both the level and the progression of muscle fatigue.

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Power analysis

Based on a hypothesised 5–10% difference in performance between hop-test conditions using the involved and non-involved leg, the number of patients required to achieve a power of 0.90 was estimated by power analysis.

Statistical methods

The intraclass correlation (ICC) coefficient was computed for analyses of the test-retest reliability of the 1 RM test, according to Shrout and Fleiss [27]. Differences in performance between fatigued and non-fatigued hop-test conditions for the involved and the non-involved side, and differences between the number of hop trials and knee-extension repetitions, were analysed using paired t-tests. The significance was considered at the α level of $p<0.05$.

Results

Hop and strength-testing symmetry

Because normal hop symmetry was required to be included in this study, all the patients had hop-index values above or equal to 90% for the hop test performed under non-fatigued conditions. However, 68% of the patients (13/19) demonstrated abnormal hop symmetry under fa-
tigued conditions (following pre-exhaustion of the quadriceps at 50% of 1 RM) when testing their ACL-reconstructed leg. The percentage of patients with abnormal 1 RM knee-extension strength scores was 63% (12/19). Eighty-four percent of the patients (16/19) exhibited abnormal symmetry in at least one of the tests (Fig. 2).

A summary of the results of the hop and strength tests is shown in Table 1. “Sensitivity” expresses the percentage of patients with ACL reconstruction who showed abnormal lower-limb symmetry values in the tests. Taken together, the sensitivity level was 0% for the non-fatigued hop test, 68% for the hop test performed under fatigued conditions, 63% for the 1 RM strength test, and 84% if we defined the patients as abnormal when at least one of the three tests showed an abnormal value.

The mean number (±SD) of repetitions of knee-extensions until failure at 50% of 1 RM was not significantly different for the involved and the non-involved leg (22±4 repetitions vs 21±3 repetitions, \(p=0.49\)). The mean number of hop trials needed to obtain three successful hops for the involved and the non-involved side under non-fatigued test conditions was 5.0 (range 3–7) and 5.7 (range 3–8) respectively, with no significant difference between sides \(p=0.08\). The number of hop trials following pre-exhaustion exercise of the quadriceps muscle at 50% of 1 RM for the involved and the non-involved side was 5.0 (range 3–9) and 4.4 (range 3–7) respectively, with no significant difference between sides \(p=0.08\).

No patients included in the study experienced pain according to the VAS at the day of the examination.

Test–retest reliability for the 1-RM test

When analysing test-retest reliability for the 1-RM knee-extension test we found excellent ICC [27] values – 0.96 – for both the involved and the non-involved leg.

**Discussion**

In addition to the single-leg hop test, which is the most commonly used test in current practice to assess knee function following ACL reconstruction [14, 25], we developed a new test in which hop performance was investigated during conditions of fatigue. We hypothesised that this method would improve the possibility to evaluate the effects of rehabilitation interventions. We found that patients with normal single-leg hop ability achieved poorer results using the involved leg when performing single-leg hops in a fatigued state. The functional disability after ACL reconstruction could therefore be better delineated by the combination of pre-exhaustion exercise followed by a single-leg hop test, rather than by a single-leg hop test alone. The higher sensitivity of the combined pre-exhaustion exercise protocol and single-leg hop test may be explained by its more-demanding, and thus more-discriminating nature when compared with non-fatigued hop testing.

There are several possible reasons for the fact that, when fatigued, patients performed worse using the involved leg during single-leg hop testing. Firstly, several studies, including this one, have demonstrated that individuals with ACL injury or reconstruction scored within a normal range during single-leg hop tests, yet showed reduced quadriceps strength [7, 11, 31]. It has been suggested that this is due to the hip and ankle extensors being capable of compensating for a knee-extension moment deficit in the involved extremity [11]. However, it is pos-

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**Table 1** Comparisons of single-leg hop performance under different test conditions and 1 RM knee-extension strength

<table>
<thead>
<tr>
<th>Test difference</th>
<th>Involved side</th>
<th>Non-involved side</th>
<th>Hop or strength</th>
<th>Percentage between sides</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-fatigued hop condition (cm)</td>
<td>141±21</td>
<td>145±22(^a)</td>
<td>97±5(^c)</td>
<td>3</td>
</tr>
<tr>
<td>Fatigued hop condition (cm)</td>
<td>109±21</td>
<td>121±21(^b)</td>
<td>89±8</td>
<td>11</td>
</tr>
<tr>
<td>1 RM strength (kg)</td>
<td>53±8</td>
<td>62±11(^b)</td>
<td>86±9</td>
<td>14</td>
</tr>
</tbody>
</table>

\(^a\)Different from involved side, \(p<0.05\)

\(^b\)Different from involved side, \(p<0.01\)

\(^c\)Different from fatigued hop index, \(p<0.01\)
sible that, during the fatigued-hop conditions in our study, the hip and ankle extensors were not able fully to compensate for the distinct quadriceps-strength deficit of the involved leg.

Another possible reason for patients performing worse using the involved leg during fatigued single-leg hop testing is that the knee joint provides the major energy-absorption function during the landing phase of the single-leg hop (J. Augustsson et al., submitted). We observed that absorbed power was two to three times greater for the knee than for the hip, and five to ten times greater for the knee than for the ankle during landing in both fatigued and non-fatigued test conditions in healthy subjects (J. Augustsson et al., submitted). The task of landing during the fatigued-hop condition, using the involved leg, therefore presumably led to great difficulties, on both a central and a peripheral level, for the patients after ACL reconstruction.

In order to assess whether a safe return to sports or strenuous work is possible following ACL reconstruction, the ability to perform functional tests of the lower extremity within normal values is regarded as an important criterion [14]. Currently, however, there is no clear consensus with regard to the definition of normal range in functional tests. For example, no single standard symmetry index is used for determining normal or abnormal maximal hop-test ability in knee rehabilitation. A ratio of limb symmetry known as the limb symmetry index (LSI) has been the most frequently reported criterion for assessing whether a hop test is normal or abnormal [1]. The LSI is used to calculate the difference in hop length between the injured and uninjured sides. An LSI of 15% – i.e. a 15% difference between limbs – is often regarded as satisfactory for single-leg hop tests [7]. However, it should be noted that these values were empirically established by noting that 90% of subjects without a history of ACL injury had LSIs greater than or equal to 85% [7]. Juris et al. [19] on the other hand, noted hop-symmetry scores of 90% for the single-leg hop test in healthy subjects. Moreover, it has been reported that in patients with ACL-deficient knees only those performing at more than 90% of knee function (including the single-leg hop test) compared with the uninjured side were able successfully to return to pre-injury levels of activity [13]. Although the degree of difference in performance between the two lower extremities has not been shown to have a definite relationship with a propensity towards injury during athletic activities [32], a difference of 10% or more can be considered to reflect a real difference in the capacity of performance [26]. Taken together, we regard a side-to-side difference of more than 10% between the involved and non-involved leg following ACL reconstruction as unsatisfactory for both hop- and strength-test scores, and believe that it may predispose a patient to overuse and/or acute injuries when returning to sports or strenuous work.

In our study, patients with ACL reconstruction exhibited a significant knee-extension 1-RM strength deficit ($p<0.01$). In accordance with this, persistent quadriceps weakness seems to be common in the ACL-reconstructed leg despite “aggressive” rehabilitation [2, 3, 8, 11, 16, 20, 22, 24, 30, 34]. In a recent study, Carter and Edinger [8] were intrigued to find that only half of the competitive athletes in their study had accomplished 80% or greater leg strength of the ACL-operated leg by 6 months after surgery, as it is customary to allow return to full activities at that time, with some authors advocating return to sports as early as 4 months after the procedure [9, 17]. In our study, 63% of the patients had residual quadriceps-muscle weakness 11 months after surgery, yet 69% had returned to their previous level of sports participation. We conclude that patients may return to sports 11 months postoperatively, but that leg strength is frequently not adequate at that time to do so without running the risk of re-injuring the knee.

We used the 1-RM test to compare the knee-extension strength of the involved and the non-involved side and found excellent test-retest reliability (the ICC value was 0.96 for the involved and the non-involved side). This is in accordance with the results of Hennessy and Watson [15], who noted high reliability for the 1-RM test for the bench press and the barbell squat exercise ($r=0.96$ and 0.97 respectively) in healthy subjects. Although the isokinetic 1-RM test is the most frequently-used tool for the evaluation of muscle strength in sports [21], strength in knee rehabilitation is almost always evaluated with isokinetic dynamometry [2, 3, 7, 8, 9, 16, 20, 23, 24, 31, 34]. However, according to several studies [4, 28, 33], isokinetic tests are not sensitive to isokinetic weight-training strength improvements. The rationale for performing isokinetic tests in clinical practice is therefore somewhat weak, as weight training during rehabilitation is typically performed using free weights and weight machines in an isotonic mode only.

The movement velocity during the exhaustive knee-extension exercise set was not controlled in our study. This is due to the fact that the cadence consistently decreases from the first to the last repetition for a subject during a set of heavy weight-training exercise [18].

**Conclusion**

Although injuries tend to occur more frequently at the end of a sporting event, when a participant is fatigued [10, 12, 35], patients are typically examined for return to sports using functional tests performed under non-fatigued conditions. This may compromise the therapist’s ability to decide whether a patient with ACL reconstruction can safely return to sports or strenuous work activities. In accordance with this, no patients in our study displayed abnormal hop symmetry when non-fatigued; however, two-thirds showed abnormal hop symmetry for the fatigued test condition. It is concluded that the pre-exhaustion exercise protocol
combined with the single-leg hop test improved testing sensitivity when evaluating lower-extremity function after ACL reconstruction. For a more realistic approach, when it comes to the functional performance testing of patients after ACL reconstruction it is suggested that these tests should be performed both under non-fatigued and fatigued test conditions.

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References


