Review Article

Functional performance testing following knee ligament injury

Nicholas C. Clark

Outcome measurement in sports physiotherapy is directed at identifying an athlete's ability to tolerate the physical demands inherent in sport-specific activity and prevent re-injury on return-to-competition. Outcome measures currently utilized following anterior cruciate ligament (ACL) injury include clinical, functional performance test (FPT), and subjective measures. The FPT simulates the forces encountered during sport-specific activity under controlled clinical conditions, the use of the FPT increasing since traditional clinical outcome measures, such as knee joint laxity and isokinetic quadriceps muscle strength, demonstrate weak to moderate and often insignificant relationships with functional tasks. Many FPTs, such as hop, leap, jump, sprint, and agility FPTs, may be administered to an athlete following knee ligament injury. However, when selecting a FPT for the assessment of knee function, the clinician must acknowledge issues relating to reliability, validity, data analysis, and at what point in the rehabilitation process a FPT should be administered if the data generated are to be meaningful and useful. Therefore, the purpose of this paper is to present a comprehensive and detailed review of the FPT literature in order to assist the sports physiotherapist with the clinical application of a FPT to an athlete following knee ligament injury.

Introduction

Outcome measurement is emphasized in physiotherapy to assess, evaluate and justify clinical practice (Chartered Society of Physiotherapy 1994; Rothstein 1985; Task Force on Standards for Measurement in Physical Therapy 1991). In sports physiotherapy, outcome measurement is also directed at identifying an athlete's ability to tolerate the physical demands inherent in sport-specific activity and prevent re-injury on return-to-competition. With regard to the knee, outcome measures currently utilized following anterior cruciate ligament (ACL) injury include clinical, functional performance test (FPT), and subjective measures. Clinical and FPT measures are popular for administration to both anterior cruciate ligament deficient (ACL-D) and anterior cruciate ligament reconstruction (ACL-R) athletes due to their ability to objectively quantify knee function (Borsa et al. 1998; Miller & Carr 1993).

Clinical measures utilized with ACL-D and ACL-R athletes include range of motion (ROM) emphasizing terminal knee extension by goniometry, passive heel lift, and prone heel height (DeCarlo et al. 1994; Sachs et al. 1989; Shelbourne & Nitz 1990), anterior tibial displacement by manual ligament testing and arthrometer (Daniel et al. 1994; Neeb et al. 1997; Sekiya et al. 1998), knee and thigh circumference (Bach et al. 1994; Clark et al. 1999; Lephart et al. 1992), isokinetic quadriceps and hamstring muscle strength (Bach et al. 1994; Lephart et al. 1992; Natri et al. 1996; Sekiya et al. 1998; Wilk et al. 1994), isometric and isotonic hip and knee extensor muscle strength (Borsa et al. 1998; Clark et al. 1999; DeCarlo et al. 1994; Hooper et al. 1998; Sekiya et al. 1998), proprioception by threshold to detection of passive motion and reflex hamstring contraction latency (Beard et al. 1994; Borsa et al. 1998; MacDonald et al. 1996; Wojtys & Huston 1994), static balance (Borsa et al. 1998; Harrison et al. 1994), and radiography (Daniel et al. 1994).

Nicholas C. Clark BEd (Hons), BSc (Hons), MCSP, CSCS, Physiotherapist, Royal Free Hospital, Royal Free Hampstead NHS Trust, Pond Street, London NW3 2QG, UK. Tel: +44 20 7794 0500, ext 4059

doi: 10.1054/ptsp.2001.0035, available online at http://www.idealibrary.com on IDEAL®

Functional performance test measures utilized with ACL-D and ACL-R athletes include hop tests (Barber et al. 1990; Brosky et al. 1999; Daniel et al. 1982; Eastlack et al. 1999; Noyes et al. 1991; Rudolph et al. 1999), leap and jump tests (Juris et al. 1997; Risberg & Ekeland 1994), and linear sprint, agility, and stair climbing tests (Barber et al. 1990; Fonseca et al. 1992; Gauffin et al. 1990; Lephart et al. 1988, 1991, 1992, 1993; Risberg & Ekeland 1994; Tegner & Lysholm 1985; Tegner et al. 1986). A hop FPT involves take-off and landing on the same leg. A leap FPT involves take-off and landing on opposite legs. A jump FPT involves take-off and landing on both legs. A running or stair climbing FPT involves the rapid cyclical alternation between legs. Consequently, hop tests are the preferred type of FPT due to utilization of the uninjured limb as a control for within-subject between-limb comparisons, and as a reference against which discharge from rehabilitation and return-to-competition may be determined (Anderson & Foreman 1996; Barber et al. 1990; Borsa et al. 1998; Daniel et al. 1982; Noyes et al. 1991; Sapega 1990). However, it should be acknowledged that a FPT may be as simple or gross a performance as desired by the clinician, such as hopping or kicking a football, respectively.

Although many FPTs, perhaps in particular a hop FPT, may not be truly sport-specific, some critics might question their use as a measurement tool. However, in the absence of sophisticated laboratory-biased kinematic and kinetic analyses (e.g. 3-D motion analysis, force plate analysis, etc), there is currently no measurement tool other than a FPT available to the sports physiotherapist for the *clinical* quantification of lower limb function.

The FPT is popular because it requires minimal space, equipment, time, and personnel for its administration in the standard clinical context (Barber et al. 1992; Keskula et al. 1996; Noyes et al. 1991), and because traditional clinical outcome measures predominantly demonstrate weak to moderate and often insignificant relationships with functional tasks in ACL-D, ACL-R, and uninjured subjects (Table 1). According to Vincent (1995), a 'strong' relationship (correlation) exists between measures (variables) when the correlation coefficient (r) is $\geqslant 0.90$ and 'significant' (i.e. $P \leqslant 0.05$). Correlation coefficients of 0.50–0.70 and 0.70–0.80 are considered 'weak' and 'moderate', respectively (Vincent 1995). If the correlation coefficient is 'insignificant' (i.e. $P > 0.05$), the relationship is due to chance and has little application to clinical practice (Greenfield et al. 1998a). However, with reference to Table 1, clinicians should not be confused by the assignment of a significant *P* value to weak or moderate correlation coefficients, since considering the *P* value alone results in misinterpretation of the relationship between variables (Di Fabio 1999). A study's assignment of a significant *P* value to a correlation coefficient has the potential to be deceptive and misleading since statistical significance and weak relationships can occur simultaneously (Di Fabio 1999). Therefore, clinicians should consider the magnitude of r before the level of significance (*P*), since it is the magnitude of r that indicates the degree to which two variables are related (Di Fabio 1999; Greenfield et al. 1998a). A significant r value does *not* automatically mean there is a strong relationship between two variables (Di Fabio 1999). Consequently, considering the predominantly weak to moderate relationships between traditional clinical outcome measures and functional tasks illustrated in Table 1, no single outcome measure is considered optimal for the evaluation of intervention following ACL injury (Borsa et al. 1998; Miller & Carr 1993; Neeb et al. 1997), and clinical outcome measures alone are considered insufficient in determining an athlete's readiness for return-to-competition (Anderson & Foreman 1996; Bandy 1992; Keskula et al. 1996).

A FPT measures joint laxity/mobility, muscle extensibility (flexibility), muscle strength and power, proprioception, neuromuscular control, dynamic balance, agility, pain, and athlete-confidence simultaneously (Anderson & Foreman 1996; Barber et al. 1992; Lephart 1994; Lephart et al. 1992; Noyes et al. 1991; Tippett & Voight 1995). Consequently, a FPT reflects a 'cumulative effect' since it is unable to identify deficits in specific variables. However, the FPT is still a useful measurement tool for the clinician because it:

- is a quantitative measure utilized to *define* function and/or outcome

Table 1 Relationship between clinical and functional performance test measures

Clinical measure	Functional performance test	Study	Subjects	r	*P*
Knee joint ROM	Shuttle sprint	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
	Semicircular manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
	Carioca manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
Prone heel height	Single hop for distance	Sachs et al. (1989)	ACL-R (n = 126)	−0.20	=0.01
Knee joint laxity	Single hop for distance	Eastlack et al. (1999)	ACL-D (n = 45)	+0.20	=0.19
		Sekiya et al. (1998)	ACL-R (n = 107)	+0.09	=0.35
	Triple hop for distance	Eastlack et al. (1999)	ACL-D (n = 45)	+0.20	=0.19
	Crossover hop for distance	Eastlack et al. (1999)	ACL-D (n = 45)	+0.20	=0.19
	Shuttle sprint	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
		Lephart et al. (1992)	ACL-D (n = 41)	−0.23	> 0.05
	Semicircular manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
		Lephart et al. (1992)	ACL-D (n = 41)	−0.21	> 0.05
	Carioca manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
		Lephart et al. (1992)	ACL-D (n = 41)	−0.27	> 0.05
Thigh circumference	Shuttle sprint	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
	Semicircular manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
	Carioca manoeuvre	Lephart et al. (1988)	ACL-D (n = 18)	+0.34	Not stated
Isokinetic quadriceps	Single jump for distance	Wiklander & Lysholm (1987)	Uninjured (n = 39)	+0.84	< 0.001
Muscle strength	Single hop for distance	Delitto et al. (1993)	ACL-R (n = 39)	+0.46	< 0.05
		Greenberger & Paterno (1994a)	Uninjured (n = 20)	+0.65	< 0.05
		Greenberger & Paterno (1995)	Uninjured (n = 20)	+0.78	< 0.05
		Noyes et al. (1991)	ACL-D (n = 67)	+0.49	< 0.001
		Ostenberg et al. (1998)	Uninjured (n = 101)	+0.42	< 0.05
		Petschnig et al. (1998)	ACL-R (n = 30)	+0.45	< 0.05
		Pincivero et al. (1997)	Uninjured (n = 37)	+0.39	< 0.05
		Sachs et al. (1989)	ACL-R (n = 126)	+0.60	=0.001
		Sekiya et al. (1998)	ACL-R (n = 107)	+0.25	=0.01
		Wilk et al. (1994)	ACL-R (n = 50)	+0.62	=0.003
	Triple hop for distance	Petschnig et al. (1998)	ACL-R (n = 30)	+0.48	< 0.05
	Crossover hop for distance	Wilk et al. (1994)	ACL-R (n = 50)	+0.69	< 0.001
	Six metre hop for time	Wilk et al. (1994)	ACL-R (n = 50)	+0.60	=0.001
	Vertical jump	Gauffin et al. (1989)	Uninjured (n = 71)	+0.40	< 0.001
		Kraemer et al. (1995)	Uninjured (n = 38)	+0.37	< 0.05
		Ostenberg et al. (1998)	Uninjured (n = 101)	+0.23	< 0.05
		Wiklander & Lysholm (1987)	Uninjured (n = 39)	+0.84	< 0.001
	Vertical hop	Delitto et al. (1993)	ACL-R (n = 39)	+0.43	< 0.05
		Petschnig et al. (1998)	ACL-R (n = 30)	+0.01	> 0.05
	Shuttle sprint	Lephart et al. (1992)	ACL-D (n = 41)	−0.42	< 0.05
	Semicircular manoeuvre	Lephart et al. (1992)	ACL-D (n = 41)	−0.20	> 0.05
	Carioca manoeuvre	Lephart et al. (1992)	ACL-D (n = 41)	−0.30	> 0.05
Isokinetic hamstring	Single jump for distance	Wiklander & Lysholm (1987)	Uninjured (n = 39)	+0.63	< 0.001
Muscle strength	Single hop for distance	Noyes et al. (1991)	ACL-D (n = 67)	+0.32	=0.02
		Pincivero et al. (1997)	Uninjured (n = 37)	+0.55	< 0.05
		Sachs et al. (1989)	ACL-R (n = 126)	+0.31	=0.001
		Sekiya et al. (1998)	ACL-R (n = 107)	+0.23	=0.02
	Vertical jump	Kraemer et al. (1995)	Uninjured (n = 38)	+0.38	< 0.05
		Wiklander & Lysholm (1987)	Uninjured (n = 39)	+0.77	< 0.001
	Shuttle sprint	Lephart et al. (1992)	ACL-D (n = 41)	−0.23	> 0.05
	Semicircular manoeuvre	Lephart et al. (1992)	ACL-D (n = 41)	−0.16	> 0.05
	Carioca manoeuvre	Lephart et al. (1992)	ACL-D (n = 41)	−0.22	> 0.05
Isometric quadriceps Muscle strength	Single hop for distance	Sekiya et al. (1998)	ACL-R (n = 58)	+0.37	< 0.01
Isometric hamstring Muscle strength	Single hop for distance	Sekiya et al. (1998)	ACL-R (n = 58)	+0.35	< 0.01
Isotonic 1RM	Single jump for distance	Blackburn & Morrissey (1998)	Uninjured (n = 20)	+0.07	> 0.05
Leg extension	Vertical jump	Blackburn & Morrissey (1998)	Uninjured (n = 20)	+0.10	> 0.05

r = Pearson product-moment correlation coefficient; *P* = Probability statement/statistical significance (Greenfield et al. 1996); ROM = Range of motion; ACL-R = Anterior cruciate ligament reconstruction subjects; ACL-D = Anterior cruciate ligament deficient subjects; 1RM = One repetition maximum.

- simulates the forces encountered during sport-specific activity under controlled clinical conditions (Barber et al. 1992; Tippett & Voight 1995).
- indirectly assesses the extent to which pain inhibits the execution of functional tasks (Barber et al. 1992; Noyes et al. 1991).
- indirectly quantifies muscle strength and power (Bandy 1992; Barber et al. 1992; Tippett & Voight 1995).
- indirectly assesses the ability of a limb to absorb force (Bandy 1992).
- indirectly assesses the ability to *dynamically* control tibial translation during the application of shearing and rotational forces to the knee (Lephart et al. 1989)
- indirectly assesses the magnitude of between-limb differences that may predispose re-injury (Bandy 1992; Barber et al. 1992; Tippett & Voight 1995).
- quantitatively assesses progress within rehabilitation (Bandy 1992; Tippett & Voight 1995).
- qualitatively assesses compensation, or asymmetry, via clinical observation (Bandy 1992; Lephart & Henry 1995; Tippett & Voight 1995).
- provides psychological reassurance to the athlete (Barber et al. 1992; Noyes et al. 1991; Tippett & Voight 1995).
- establishes sport-specific, position-specific, and within-group normative data (Davies 1995; Tippet & Voight 1995).
- correlates ($r = 0.62–0.75$, $P < 0.05$) with subjective assessment of knee function (Goh & Boyle 1997).

When selecting a FPT the clinician must acknowledge issues relating to reliability, validity, data analysis and at what point in the rehabilitation process a FPT should be administered if the data generated are to be meaningful and useful. These issues are critical if an athlete is to safely return-to-competition and the risk of re-injury is to be minimized. Therefore, the purpose of this paper is to present a comprehensive and detailed review of the literature in order to assist the sports physiotherapist with the selection and clinical application of a FPT for an athlete with knee ligament injury.

Reliability

Reliability refers to whether a specific measurement protocol, also termed 'operational definition' (Rothstein 1985, 1993), minimizes measurement error (i.e. systematic and/or random error) producing *accurate* and *consistent* measurements during repeated measures of the same variable (Atkinson & Nevill 1998; Greenfield et al. 1998b; Krebs 1987; Portney & Watkins 1993; Rothstein 1985, 1993). Simply, 'reliability' is an indication of a measurement protocol's *standardization* (Jones 1991; Rothstein 1985). For example, will a measurement protocol produce accurate and consistent results if the *same* clinician performs the measurement on separate occasions (*intra*tester reliability), or if a *different* clinician performs the measurement on separate occasions (*inter*tester reliability)? For the sports physiotherapist, 'high' measurement reliability as a result of strictly standardized measurement protocols is critical if *criteria*-based return-to-competition decisions potentially result from the *objective* data generated following the administration of a FPT. The reliability of selected FPTs utilized in the assessment of lower limb function is illustrated in Table 2.

The Intraclass Correlation Coefficient (ICC) is currently the recommended convention for quantifying measurement reliability (Denegar & Ball 1993; Portney & Watkins 1993), with an ICC $\geqslant 0.90$ considered indicative of 'highly' reliable clinical measurement protocols (Portney & Watkins 1993). However, there are six 'forms' of ICC (Portney & Watkins 1993; Shrout & Fleiss 1979), with the selected form potentially affecting the magnitude of the final ICC value (Denegar & Ball 1993; Krebs 1984, 1986; Portney & Watkins 1993). This, in turn, has the potential to influence whether clinicians interpret a measurement protocol as being appropriately 'standardized'. Thus, clinicians should familiarize themselves with the concept of measurement reliability, since the implications of a FPT which is assigned an 'inflated' ICC due utilization of the incorrect 'form' include an athlete's re-injury due to inaccurate measurements and invalid data, and a premature return-to-competition. Detailed discussions of reliability in sports medicine are

Table 2 Reliability of selected functional performance tests

Test	Study	Subjects	Reliability
Single jump for distance	Johnson & Nelson (1979)	Uninjured (n not stated)	0.96^{ICC}
Single hop for distance	Bandy et al. (1994)	Uninjured (n = 18)	0.93^{ICC}
	Bolgla & Keskula (1997)	Uninjured (n = 20)	0.96^{ICC}
	Booher et al. (1993)	Uninjured (n = 18)	0.97^{ICC}
	Brosky et al. (1999)	ACL-R (n = 15)	0.97^{ICC}
	Greenberger & Paterno (1994b)	Uninjured (n = 20)	0.96^{ICC}
	Hu et al. (1992)	Uninjured (n = 30)	0.96^{ICC}
	Kramer et al. (1992)	ACL-R (n = 38)	0.93^{ICC}
	Paterno & Greenberger (1996)	Uninjured (n = 20)	0.96^{ICC}
	Paterno & Greenberger (1996)	ACL-R (n = 13)	0.89^{ICC}
	Worrell et al. (1993)	Uninjured (n = 36)	0.99^{ICC}
Triple hop for distance	Bandy et al. (1994)	Uninjured (n = 18)	0.94^{ICC}
	Bolgla & Keskula (1997)	Uninjured (n = 20)	0.95^{ICC}
Crossover hop for distance	Bandy et al. (1994)	Uninjured (n = 18)	0.90^{ICC}
	Bolgla & Keskula (1997)	Uninjured (n = 20)	0.96^{ICC}
	Goh & Boyle (1997)	Uninjured (n = 10)	0.85^{ICC}
Adapted crossover hop for distance	Clark et al. (1999)	Uninjured (n = 12)	0.94^{ICC}
Six metre hop for time	Bolgla & Keskula (1997)	Uninjured (n = 20)	0.66^{ICC}
	Booher et al. (1993)	Uninjured (n = 18)	0.77^{ICC}
	Brosky et al. (1999)	ACL-R (n = 15)	0.97^{ICC}
	Worrell et al. (1993)	Uninjured (n = 36)	0.77^{ICC}
Twelve metre hop for time	Goh & Boyle (1997)	Uninjured (n = 10)	0.96^{ICC}
Ten feet hop for time	Bandy et al. (1994)	Uninjured (n = 18)	0.92^{ICC}
Thirty metre agility hop for time	Booher et al. (1993)	Uninjured (n = 18)	0.09^{ICC}
Vertical jump	Bocchinfuso et al. (1994)	Uninjured (n = 15)	0.99^{ICC}
	Johnson & Nelson (1979)	Uninjured (n not stated)	0.93^{ICC}
	Kraemer et al. (1995)	Uninjured (n = 38)	0.97^{r}
	Locke et al. (1997)	Uninjured (n = 11)	0.98^{ICC}
	Thomas et al. (1996)	Uninjured (n = 19)	0.95^{ICC}
Vertical hop	Bandy et al. (1994)	Uninjured (n = 18)	0.85^{ICC}
	Brosky et al. (1999)	ACL-R (n = 15)	0.97^{ICC}
	Clark et al. (1999)	Uninjured (n = 12)	0.94^{ICC}
	Hu et al. (1992)	Uninjured (n = 30)	0.96^{ICC}
	Petschnig et al. (1998)	Uninjured (n = 50)	0.89^{ICC}
	Risberg et al. (1995)	Uninjured (n = 21)	0.95^{r}
Stairs hop for time	Goh & Boyle (1997)	Uninjured (n = 10)	0.94^{ICC}
	Risberg et al. (1995)	Uninjured (n = 21)	0.81^{r}
Linear sprint	Bocchinfuso et al. (1994)	Uninjured (n = 15)	0.85^{ICC}
	Kraemer et al. (1995)	Uninjured (n = 38)	0.98^{r}
	Locke et al. (1997)	Uninjured (n = 11)	0.96^{ICC}
	Thomas et al. (1996)	Uninjured (n = 19)	0.99^{ICC}
Shuttle sprint	Bocchinfuso et al. (1994)	Uninjured (n = 15)	0.99^{ICC}
	Lephart et al. (1991)	ACL-D (n = 18)	0.96^{ICC}
	Locke et al. (1997)	Uninjured (n = 11)	0.90^{ICC}
Agility sprint	Anderson et al. (1991)	Uninjured (n = 9)	0.95^{ICC}
	Bocchinfuso et al. (1994)	Uninjured (n = 15)	0.98^{ICC}
	Risberg et al. (1995)	Uninjured (n = 21)	0.81^{r}
Cybex reactor® Agility task	Hertel et al. (1999)	Uninjured (n = 13)	0.68^{ICC}
Semicircular Manoeuvre	Lephart et al. (1991)	ACL-D (n = 18)	0.96^{ICC}
Carioca Manoeuvre	Lephart et al. (1991)	ACL-D (n = 18)	0.96^{ICC}

ACL-R = Anterior cruciate ligament reconstruction subjects; ACL-D = Anterior cruciate ligament deficient subjects; ICC = Intraclass correlation coefficient; r = Pearson product-moment correlation coefficient.

presented by Atkinson and Nevill (1998), and Denegar and Ball (1993).

Furthermore, although Table 2 also illustrates examples of the Pearson Product-Moment Correlation Coefficient (r) for quantifying FPT reliability, clinicians are reminded that r is a *bivariate* statistic which consistently overestimates reliability due to its inappropriate application to *univariate* data (Atkinson & Nevill 1998; Denegar & Ball 1993; Portney & Watkins 1993; Vincent 1995). Therefore, studies which employ r to quantify reliability also result in inflated correlation coefficients and should be interpreted with caution.

Validity

According to Anderson and Foreman (1996), Barber et al. (1990), and Risberg and Ekeland (1994), the validity of existing FPTs of knee function has yet to be established. Validity refers to whether a measurement protocol actually measures the variable it is intended to measure (Gould 1994; Greenfield et al. 1998b; Krebs 1987; Portney & Watkins 1993; Rothstein 1985, 1993). For example, are active knee extension goniometry or mid-thigh circumference valid measures of quadriceps muscle strength?

There are four types of measurement validity: *face* validity, *construct* validity, *content* validity, and *criteria-related* validity (Gould 1994; Portney & Watkins 1993; Rothstein 1985, 1993). Face validity refers to whether a measurement protocol *appears* to measure the variable of interest, being based purely on clinicians' opinions rather than scientific evidence (Rothstein 1985). For example, is an isokinetic dynamometer a 'face valid' measure of muscle strength?

Construct validity refers to the inference a measurement protocol is valid based on scientific hypothesis, being a theoretical form of validity (Rothstein 1985, 1993). It is the 'idea' underlying the measurement protocol. For example, due to the many different ways in which muscles can express force (Mayhew & Rothstein 1985), a deliberately non-specific definition of 'muscle strength' is the ability of a muscle to produce force. Therefore, a measurement tool which quantifies the amount of force a muscle produces could, in turn, be considered a valid measure of muscle strength. Since isokinetic dynamometers *indirectly* measure the amount of force a muscle produces via a computer-configured strain-gauge or load-cell (Dvir 1995; Kannus 1994; Mayhew & Rothstein 1985; Perrin 1993), isokinetic dynamometers may be considered a 'construct valid' measure of muscle strength.

Content validity refers to whether a measurement protocol is valid based on its ability to reflect the variable of interest, also being a theoretical form of validity (Rothstein 1985, 1993). Essentially, once the idea has been formed that a specific variable can be measured in a specific way (construct validity), does the measurement protocol reflect accepted units of measurement (e.g. newton-metres) associated with the variable of interest? For example, muscles produce force as they induce joint rotations, dynamic rotational force (torque) is quantified in newton-metres (Publications Advisory Committee 1992), and isokinetic dynamometers utilize newton-metres (Nm) as their units of measurement (Dvir 1995; Kannus 1994; Perrin 1993). Therefore, isokinetic dynamometers may also be considered a 'content valid' measure of dynamic muscle strength, quantified in Nm.

Criteria-related validity refers to whether a measurement protocol may be considered valid when compared to specific scientific criteria (Rothstein 1985, 1993). For example, with further reference to isokinetic dynamometry, a criteria for assessing its validity as a measure of muscle strength might be the mode of muscle action during sport-specific activity. Muscles produce force via isometric and isotonic muscle actions during muscle function in sport, *never* isokinetic muscle actions. Therefore, although isokinetic dynamometry appears to demonstrate face, construct, and content validity, how can it be a truly valid measure of 'functional' muscle strength if the only time muscles produce force via isokinetic muscle actions is when they are applied against an isokinetic dynamometer? Subsequently, it appears that isokinetic dynamometry is not a truly valid measure of functional muscle strength since it lacks fundamental muscle physiology-based criteria-related validity. This may explain the predominantly weak to moderate, and often insignificant, relationship between isokinetic thigh muscle strength and many FPTs (Table 1).

Clearly, validity is a critical concept for the clinician when selecting a FPT. At present, the validity of a FPT can be considered from two predominant perspectives.

First, with regard to biomechanics. Laboratory based kinematic and kinetic analyses have demonstrated the knee contributes 49–56% to a *vertical* FPT (Hubley & Wells 1983; Luhtanen & Komi 1978; Morrissey 1994), but only 3.9% to a *horizontal* FPT (Robertson & Fleming 1987). Thus, horizontal FPTs (e.g. single hop for distance) may not be the most valid measure of knee function with regard to established biomechanical data. This is an example of how horizontal FPTs fail to demonstrate criteria-related validity, the criteria being known knee joint contributions to horizontal vs vertical athletic performance.

Second, with regard to *sensitivity* and *specificity*, and the ability of a FPT to identify dysfunctional knees. Sensitivity refers to the ability of a measurement protocol to detect the 'real' presence of a suspected condition (e.g. mechanical/functional knee instability), and obtain a 'true-positive' result (Portney & Watkins 1993; Wojtys et al. 1996). Specificity refers to the ability of a measurement protocol to detect the 'real' absence of a suspected condition and obtain a 'true-negative' result (Portney & Watkins 1993; Wojtys et al. 1996).

The sensitivity and specificity of a FPT can be hypothesized by the apparent physical demands of a FPT, or its face validity. For example, Anderson and Foreman (1996), suggest the crossover hop for distance, originally described by Noyes et al. (1991), to be a more sensitive measure of knee function than other hop tests since it imposes both frontal plane and rotational forces on the knee in addition to the predominantly saggital plane forces displayed by the majority of horizontal FPTs. Preliminary evidence in support of this suggestion has recently been presented by Eastlack et al. (1999), who report the crossover hop for distance as being more discriminate of 'copers' vs 'non-copers' in ACL-D athletes ($n = 45$) than the single hop for distance, triple hop for distance, or 6 m hop for time. Furthermore, Clark (1998), has identified a between-limb trend ($P = 0.056$) for the single hop for distance, but a between-limb significant difference ($P = 0.014$) for a modified crossover hop for distance in a group of ACL-R subjects ($n = 10$), concluding the modified crossover hop for distance to be a more sensitive measure for detecting between-limb differences. This is an example of how the crossover hop for distance apparently succeeds in demonstrating a specific criteria-related validity, the criteria being a between-limb significant difference ($P < 0.05$) based on performance of the uninjured limb as a control. Thus, the process of data analysis can also contribute to the apparent sensitivity of a FPT. This is considered in more detail in the next section.

Determining whether a FPT is a valid measure of knee function is clearly a complex issue. At present there is no consensus in the literature. Therefore, when selecting a specific FPT for the assessment of knee function, clinicians must decide how to *define* validity: whether to consider knee joint contributions to specific tasks (i.e. horizontal vs vertical), or whether to consider a FPT's ability to detect between-limb differences? To complicate matters further, it is beginning to become apparent that some FPTs, such as the vertical hop, are considered more suitable for measuring force *production* at the knee (Clark et al. 1999), whilst others, such as the single hop for distance, are considered more suitable for measuring force *absorption* at the knee (Juris et al. 1997).

Clearly, much research is needed to determine which FPTs are optimal for assessing which variables of knee function. In fact, research is first needed to determine which variables (e.g. joint laxity, muscle strength, proprioception, neuromuscular control, dynamic balance, etc), most influence, or have the strongest relationship to, the successful execution of a FPT. A paradigm for the criteria-related validity of the FPT has yet to be established.

Data analysis

Depending upon the FPT which is selected, lower limb function is indirectly quantified utilizing distance (e.g. single hop for distance), or time (e.g. 6 m hop for time). Thus, data which is generated from the execution of a FPT reflects the distance achieved following the performance of a specified task, or the time taken to perform a specified task. Depending upon the number of trials which the athlete performs, the clinician has the option of utilizing maximum distance, minimum time, or mean distance or mean time as raw data for data analysis. However, significant differences ($P < 0.01$) have been identified for the final criterion measurement depending upon whether a maximum value (i.e. 'best' of three trials), or mean value (i.e. mean of three trials), is employed as raw data (Kramer et al. 1992). The author suggests the athlete's 'best' value is utilized as raw data since recent research demonstrated that maximum hop distance was consistently achieved on the third of three trials for the single hop for distance and a modified crossover hop for distance, being attributed to a warm-up, learning, and confidence effect (Clark 1998), and because it seems logical the athlete's 'best' performance is measured if return-to-competition inferences potentially result from the administration of a FPT.

The literature illustrates that hop FPT raw data may be examined utilizing two predominant methods of data analysis: a paired *t*-test in relation to within-subject between-limb significant differences (Barber et al. 1990; Gauffin et al. 1990; Paterno & Greenberger 1996; Risberg & Ekeland 1994; Tegner et al. 1986), or a limb symmetry index (Fig. 1) in relation to normative data (Barber et al. 1990; Daniel et al. 1982; Juris et al. 1997; Kramer et al. 1992; Noyes et al. 1991; Petschnig et al. 1998).

With regard to statistical analysis, several authors have detected between-limb significant differences ($P < 0.05$) for the single hop for distance (Barber et al. 1990; Gauffin et al. 1990; Paterno & Greenberger 1996; Risberg & Ekeland 1994; Tegner et al. 1986), crossover hop for distance (Eastlack et al. 1999), and a modified crossover hop for distance (Clark 1998).

With regard to a limb symmetry index (LSI) current data suggests that 'normal' knee function exists with a LSI $\geqslant$ 85% (Barber et al. 1990), or $\geqslant$90% (Daniel et al. 1982; Petschnig et al. 1998). However, Barber et al. (1990), and Noyes et al. (1991), concluded the single hop for distance, triple hop for distance, 6 m hop for time, and crossover hop for distance were insensitive measures of knee function since 50% of ACL-D subjects achieved a LSI $\geqslant$ 85%. In addition, Barber et al. (1990), also concluded the vertical hop was insensitive since 27% of *uninjured* subjects achieved a LSI $\leqslant$ 80%, and that two types of shuttle run were also insensitive since 90% of ACL-D subjects achieved a LSI $\geqslant$ 85%. Yet, in contrast to Barber et al. (1990), other authors consider the vertical hop is a sensitive measure of knee function since 100% of ACL-R subjects achieved a LSI $\leqslant$ 85% at 13 and 54 weeks post-surgery (Petschnig et al. 1998).

The LSI is useful to the clinician since it can be quickly and easily calculated (Fig. 1) in the absence of statistical software, and because it utilizes the uninjured limb as a control for within-subject between-limb comparisons (Anderson & Foreman 1996; Barber et al. 1990; Borsa et al. 1998; Daniel et al. 1982; Noyes et al. 1991; Sapega 1990), generating a single unit (%) potentially indicative of injured limb deficits. However, clinicians should acknowledge three assumptions underlying the application of the LSI. First, the assumption the control (uninjured) limb is 'normal' in relation to the variables being measured within a FPT (e.g. joint laxity, muscle strength, proprioception, dynamic balance, etc). Second, the assumption the control limb has not undergone a significant 'detraining-effect' secondary to reduced physical activity as a consequence of the injured limb. Third, there is no effect of limb dominance (e.g. 'stronger' limb vs 'weaker' limb). With regard to normative data, 'norm tables' for variables such as unilateral lower limb muscle strength, proprioception, and dynamic balance are noticeably absent from the literature. With regard to detraining of the control limb, the existence of such an effect can only be established in relation to baseline data collected during pre-participation screening.

$$\textbf{LSI (\%)} = \textbf{injured limb score} \div \textbf{uninjured limb score} \times \textbf{100}$$

Fig. 1 Calculation of Limb Symmetry Index (LSI) (adapted from Barber et al. 1990; Sapega 1990).

With regard to limb dominance, several authors have failed to identify between-limb significant differences ($P > 0.05$) for isokinetic muscle strength (Guadagnoli et al. 1998; Szczerba et al. 1995), proprioception (Guadagnoli et al. 1998), balance (Guadagnoli et al. 1998; Harrison et al. 1994; Hoffman et al. 1998; Szczerba et al. 1995), or motor skill (Beling et al. 1998; Guadagnoli et al. 1998), in uninjured subjects. Therefore, providing the athlete has no history of pathology or detraining in the 'uninjured' limb, and since a dominance effect has yet to be proven in the literature, the clinician can be confident in the utilization of the uninjured limb as a control for data analysis employing the LSI.

Screening criteria prior to initiating functional performance testing

A concept which is surprisingly scarce in the neuromusculoskeletal literature is at what point in the rehabilitation process a FPT should first be administered. Some authors suggest immediately post-injury (Tippett & Voight 1995). However, prior to administering a FPT, it is judicious of the clinician to implement 'screening criteria' which are intended to ensure the knee is able to tolerate the forces inherent in a FPT, minimizing the risk of re-injury and progressing rehabilitation toward more sport-specific activities. Essentially, the athlete's readiness to safely execute a FPT must first in itself be tested. Despite the weak to moderate relationships illustrated in Table 1, the sports physiotherapist can only employ traditional *clinical* measurement tools to obtain the data utilized as *objective* screening criteria to this end.

According to Barber et al. (1992), DeMaio et al. (1992), and Lephart and Henry (1995), a FPT should not be administered until any pain, effusion, and crepitus are absent, and the knee demonstrates a full active ROM, emphasizing terminal knee extension (Shelbourne & Nitz 1990). Gait including stair ascent and descent should appear symmetrical during clinical observation (Barber et al. 1992; DeMaio et al. 1992; Lephart & Henry 1995).

With regard to muscle strength, Shelbourne and Nitz (1990), indicate that agility-biased activities may be initiated following ACL-R when an isokinetic quadriceps LSI $\geqslant 70\%$ is demonstrated. This is in contrast to Sapega (1990), who considers a LSI $\leqslant 80\%$ in *uninjured* subjects to be abnormal, regardless of the muscle group being tested or the mode of muscle action. More recently, Barber et al. (1992), have assigned an isokinetic quadriceps LSI $\geqslant 85\%$ as a screening criteria prior to administering a FPT following ACL-R, whilst DeMaio et al. (1992), and Mangine et al. (1992), have utilized a multi-angle isometric manual muscle test (MMT) of the hip and knee prime movers in the early stage of rehabilitation following ACL-R. An isometric MMT grade 4 is considered acceptable (Mangine et al. 1992). However, clinicians should be aware the MMT is notoriously unreliable (Lamb 1985; Sapega 1990), and that the validity of a grade 4 MMT score has recently been questioned (Dvir 1997). Therefore, the recommendations of DeMaio et al. (1992), and Mangine et al. (1992), should be adopted with caution. Furthermore, when assessing ACL-injured athletes, it is advised that clinicians perform any inner range quadriceps isometric MMT with a proximal tibial hand placement to minimize anterior shear of the tibia on the femur (Jurist & Otis 1985; Wilk & Andrews 1993).

Since many FPTs utilize the stretch-shortening cycle (Allerheiligen 1994; Chu 1992, 1993), the author suggests that pre-participation screening criteria originally designed to prevent injury within plyometric conditioning programmes may be adapted for use with injured athletes prior to the administration of a FPT. Such pre-participation screening criteria have been developed by Chu (1992, 1993), Voight et al. (1995), and Voight and Tippett (1994).

Chu (1992), Voight et al. (1995), and Voight and Tippett (1994), indicate that some authorities consider the successful execution of a one repetition maximum (1RM) squat at 150–200% of bodyweight (BW) to be an appropriate criteria for initiating plyometric conditioning. However, Voight and Tippett (1994), consider this minimum criteria inappropriate and unnecessarily high. Consequently, Chu (1992, 1993), utilizes both a 1RM squat at $\geqslant 75\%$ BW, and a timed five repetition maximum (5RM) squat at $\geqslant 60\%$ BW in 5 seconds, as two criteria for initiating lower limb plyometrics. Yet, it must be remembered that these criteria refer to *uninjured* athletes executing a *bilateral* lower limb muscle strength test. Therefore, since *unilateral* FPTs are preferred for within-subject between-limb comparisons (Anderson & Foreman 1996; Barber et al. 1990; Noyes et al. 1991; Petschnig et al. 1998), and demand high levels of lower limb extensor muscle strength relative to BW, the author suggests a unilateral muscle strength test such as a 1RM single leg press, from 90° to 0° knee flexion, with correct lower limb alignment, controlled concentric *and* eccentric phases, and an involved limb relative strength index (RSI) $\geqslant$ 125%, as a more appropriate minimum criteria for *injured* athletes. Reliability for such a protocol ($n = 12$) has been established as high: ICC (2, 1) = 0.94, standard error of measurement (SEM) = 9.7 kg (Clark et al. 1999). The RSI (Fig. 2) for the injured or uninjured limb is calculated by dividing absolute strength or weight pushed (kg) by BW (kg) and multiplying the result by 100 to yield a percentage (Dick 1989; Heyward 1998). In the absence of a leg press resistance machine, this test may be adapted into a step-up test with added external resistance (e.g. hand-weights). An example of such a test has been devised by Worrell et al. (1993).

Voight et al. (1995), and Voight and Tippett (1994), have developed 'Plyometric Static Stability Testing'. Plyometric Static Stability Testing involves a progression of three simple tests: single leg stance, isometric single leg quarter-squat, and isometric single leg half-squat (Voight et al. 1995; Voight & Tippett 1994). Each test is maintained for a minimum of 30 seconds, first with eyes open and then with eyes closed (Voight et al. 1995; Voight & Tippett 1994). The athlete is observed for correct lower limb alignment and 'shaking' or 'trembling' of specific muscles (Voight et al. 1995; Voight & Tippett 1994). If poor lower limb alignment is demonstrated through excessive joint movement in a specific direction, the prime movers and synergists responsible for movement in the *opposite* direction should be assessed for muscle weakness (Voight et al. 1995; Voight & Tippett 1994). Such a strategy encompasses the concept of proximal stability and muscle balance throughout the lower limb (Alexander & Silvester 1999), which may be critical in enhancing knee function and preventing re-injury since proximal lower limb muscle dysfunction is evident secondary to distal lower limb ligamentous injury (Bullock-Saxton 1994). Furthermore, since Voight et al. (1995), and Voight and Tippett (1994), have limited Plyometric Static Stability Testing to 30 seconds for uninjured athletes, the author suggests an arbitrary increase of 50% to 45 seconds may be appropriate for injured athletes.

Table 3 summarizes *clinical* screening criteria for initiating a FPT. It may not be necessary to utilize all of the criteria suggested in Table 3, but the clinician is encouraged to select a battery of criteria which are thought to be most rigorous according to the perceived physical demands of the intended FPT. Although, as discussed previously, the reliability and validity of the MMT has been questioned, the MMT is included in Table 3 according to recommendations in the literature (DeMaio et al. 1992; Mangine et al. 1992), since there will always a need for the practical and economical quantification of muscle strength in the standard *clinical* context (Sapega 1990). Furthermore, the author has deliberately excluded isokinetic measurement of muscle strength from Table 3 since isokinetic dynamometers are uncommon *clinical* measurement tools, and since weak to moderate and often insignificant relationships exist between isokinetic muscle strength and many FPTs (Table 1). Clinicians should decide for themselves whether the inclusion of the MMT and exclusion of isokinetic dynamometry from Table 3 is appropriate or justifiable for *clinical* practice.

Summary

Outcome measurement in sports physiotherapy is directed at identifying an athlete's ability to tolerate the physical demands inherent in

$$\textbf{RSI (\%)} = \textbf{weight pushed (kg)} \div \textbf{bodyweight (kg)} \times \textbf{100}$$

Fig. 2 Calculation of Relative Strength Index (RSI) (adapted from Dick 1989; Heyward 1998).

Table 3 Suggested clinical screening criteria for functional performance testing*

No pain
No effusion
No crepitus
Full active ROM emphasizing terminal knee extension
Symmetrical gait including stair ascent and stair descent qualitatively assessed via clinical observation
Hip and ankle prime mover multi-angle isometric MMT $\geqslant$ grade 4
Quadriceps multi-angle isometric MMT $\geqslant$ grade 4 with proximal tibial hand placement
Lower limb extensor muscle strength LSI $\geqslant$ 85%
1RM single leg press RSI $\geqslant$ 125% with controlled concentric and eccentric phases
Single leg stance $\geqslant$ 45 seconds with eyes open and eyes closed
Isometric single leg quarter-squat $\geqslant$ 45 seconds with eyes open and eyes closed
Isometric single leg half-squat $\geqslant$ 45 seconds with eyes open and eyes closed

*Adapted from: Barber et al. (1992), DeMaio et al. (1992), Jurist & Otis (1985), Heyward (1998), Lephart & Henry (1995), Mangine et al. (1992), Shelbourne & Nitz (1990), Voight et al. (1995), Voight & Tippett (1994), Wilk & Andrews (1993).

ROM = range of motion; MMT = manual muscle test; LSI = limb symmetry index (injured limb score ÷ uninjured limb score × 100); 1RM = one repetition maximum; RSI = relative strength index (weight pushed [kg] ÷ bodyweight [kg] × 100).

sport-specific activity and prevent re-injury on return-to-competition. Many clinical and FPT measures are available to the clinician for the objective assessment of knee function. The FPT is becoming more popular because traditional clinical outcome measures demonstrate weak to moderate and often insignificant relationships to functional tasks (Table 1). Furthermore, of the FPTs available to the clinician (Table 2), hop FPTs are preferred due to utilization of the uninjured limb as a control against which return to competition may be determined. Although hop tests may not be truly sport-specific, they simulate the forces encountered during sport-specific activity under controlled conditions, and are currently the best measurement tool for the clinical assessment of lower limb function in the absence of sophisticated laboratory-biased biomechanical analyses.

When selecting a FPT the clinician must acknowledge issues relating to reliability, validity, data analysis, and at what point in the rehabilitation process a FPT should be administered if an athlete is to safely return-to-competition and the risk of re-injury is to be minimized.

Many FPTs are highly reliable (Table 2), although their validity is a contentious issue and has yet to be definitively established in the literature. However, preliminary evidence of the criteria-related validity of some specific FPTs (e.g. crossover hop for distance) for detecting knee dysfunction is now emerging. The LSI (Fig. 1) is the easiest method of data analysis in the absence of statistical software. Clinicians can be confident in the application of the LSI providing there is no history of pathology or detraining in the 'uninjured' limb, and since a dominance effect has yet to be proven in the literature. Prior to the administration of a FPT, the clinician must first assess the athlete's ability to tolerate the forces inherent in a FPT, further minimizing the risk of re-injury and progressing rehabilitation toward more sport-specific activities. Objective screening criteria utilizing traditional clinical outcome measures have been suggested to this end (Table 3).

Functional performance tests have the potential to yield valuable information to the clinician regarding an athlete's status following knee ligament injury. Therefore, clinicians should familiarize themselves with the issues discussed previously if the appropriate selection and clinical application of a FPT is intended. Although the literature cited in this paper almost exclusively refers to an ACL-injured population, which is a reflection of the literature rather than a preference of the author, it is suggested the issues discussed in this paper may be extrapolated to other types of knee ligament injury (e.g. medial collateral ligament, posterior cruciate ligament, etc).

Acknowledgements

This paper is an extension of work which was originally performed for a Nuffield Foundation

Student Research Scholarship (AT/100/98/0279) when the author was an undergraduate student with the Human Motion and Performance Laboratory of the Department of Health Sciences at the University of East London, UK. Many thanks to Zoe Hudson GradAssocPhys, MCSP, SRP, and Dr Matthew Morrissey ScD, PT, for their encouragement to prepare this paper.

References

Alexander M, Silvester M 1999 Muscle Imbalances Relating to Lower Limb Injuries in Sport. Course Notes. Association of Chartered Physiotherapists in Sports Medicine and London Broncos Rugby League Football Club. London, UK

Allerheiligen W 1994 Speed development and plyometric training. In: Baechle T (ed). Essentials of Strength Training and Conditioning. Human Kinetics, Illinois, ch 20, pp 314–344

Anderson M, Foreman T 1996 Return to competition: functional rehabilitation. In: Zachazewski J, Magee D, Quillen W (eds). Athletic Injuries and Rehabilitation. WB Saunders Company, Philadelphia, ch 13, pp 229–261

Anderson M, Gieck J, Perrin D, Weltman A, Rutt R, Denegar C 1991 The relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and three components of athletic performance. Journal of Orthopaedic and Sports Physical Therapy 14 (3): 114–120

Atkinson G, Nevill A 1998 Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. Sports Medicine 26 (4): 217–238

Bach B, Jones T, Sweet F, Hager C 1994 Arthroscopy-assisted anterior cruciate ligament reconstruction using patellar tendon substitution: two to four year follow-up. American Journal of Sports Medicine 22 (6): 758–767

Bandy W 1992 Functional rehabilitation of the athlete. Orthopaedic Physical Therapy Clinics of North America 1 (2): 269–281

Bandy W, Rusche K, Tekulve F 1994 Reliability and limb symmetry for five unilateral functional tests of the lower extremities. Isokinetics and Exercise Science 4 (3): 108–111

Barber S, Noyes F, Mangine R, DeMaio M 1992 Rehabilitation after ACL reconstruction: function testing. Orthopedics 15 (8): 969–974

Barber S, Noyes F, Mangine R, McCloskey J, Hartman W 1990 Quantitative assessment of functional limitations in normal and anterior cruciate ligament deficient knees. Clinical Orthopaedics and Related Research 255: 204–214

Beard D, Kyberd P, O'Connor J, Fergusson C, Dodd C 1994 Reflex hamstring contraction latency in anterior cruciate ligament deficiency. Journal of Orthopaedic Research 12: 219–228

Beling J, Wolfe G, Allen K, Boyle J 1998 Lower extremity preference during gross and fine motor skills in sitting and standing postures. Journal of Orthopaedic and Sports Physical Therapy 28 (6): 400–404

Blackburn J, Morrissey M 1998 The relationship between open and closed kinetic chain strength of the lower limb and jumping performance. Journal of Orthopaedic and Sports Physical Therapy 27 (6): 430–435

Bocchinfuso C, Sitler M, Kimura I 1994 Effects of two semirigid prophylactic ankle stabilizers on speed, agility, and vertical jump. Journal of Sport Rehabilitation 3 (2): 125–134

Bolgla L, Keskula D 1997 Reliability of lower extremity functional performance tests. Journal of Orthopaedic and Sports Physical Therapy 26 (3): 138–142

Booher L, Hench K, Worrell T, Stikeleather J 1993 Reliability of three single leg hop tests. Journal of Sport Rehabilitation 2: 165–170

Borsa P, Lephart S, Irrgang J 1998 Comparison of performance-based and patient-reported measures of function in anterior cruciate ligament deficient individuals. Journal of Orthopaedic and Sports Physical Therapy 28 (6): 392–399

Brosky J, Nitz A, Malone T, Caborn D, Rayens M 1999 Intrarater reliability of selected clinical outcome measures following anterior cruciate ligament reconstruction. Journal of Orthopaedic and Sports Physical Therapy 29 (1): 39–48

Bullock-Saxton J 1994 Local sensation changes and altered hip muscle function following severe ankle sprain. Physical Therapy 74 (1): 17–31

Chartered Society of Physiotherapy 1994 Standards for administering tests and taking measurements. Chartered Society of Physiotherapy, London, UK

Chu D 1992 Jumping into Plyometrics. Human Kinetics, Illinois

Chu D 1993 Jumping into Plyometrics Video. Human Kinetics, Illinois

Clark N 1998 . The Long-Term Effects of Different Resistance Training Programmes in Rehabilitation After Anterior Cruciate Ligament Reconstruction. Nuffield Foundation Student Research Scholarship AT/100/98/0279. Human Motion and Performance Laboratory. Department of Health Sciences. University of East London. London, UK

Clark N, Gumbrell C, Rana S, Traole C 1999 . The Correlation of Short-Term Clinical Measures After Anterior Cruciate Ligament Reconstruction to Long-Term Outcome. Bachelor of Science Physiotherapy Dissertation. Department of Health Sciences. University of East London. London, UK

Daniel D, Malcolm L, Stone M, Perth H, Morgan J, Riehl B 1982 Quantification of knee stability and function. Contemporary Orthopaedics 5 (1): 83–91

Daniel D, Stone M, Dobson B, Fithian D, Rossman D, Kaufman K 1994 Fate of the ACL injured patient: a prospective outcome study. American Journal of Sports Medicine 22 (5): 632–644

Davies G 1995 The need for critical thinking in rehabilitation. Journal of Sport Rehabilitation 4 (1): 1–22

DeCarlo M, Sell K, Shelbourne K 1994 Current concepts in accelerated ACL rehabilitation. Journal of Sport Rehabilitation 3 (4): 304–318

Delitto A, Irrgang J, Harner C, Fu F, Nessi S 1993 Relationship of isokinetic quadriceps peak torque and work to one legged hop and vertical jump in ACL reconstructed subjects (Abstract). Physical Therapy 73 (6) Supplement: S85

DeMaio M, Mangine R, Noyes F, Barber S 1992 Advanced muscle training after ACL reconstruction: weeks 6 to 52. Orthopedics 15 (6): 757–767

Denegar C, Ball D 1993 Assessing reliability and precision of measurement: an introduction to intraclass correlation and standard error of measurement. Journal of Sport Rehabilitation 2 (1): 35–42

Dick F 1989 Sports Training Principles, 2nd edn. A & C Black, London

Di Fabio R 1999 Significance of relationships. Journal of Orthopaedic and Sports Physical Therapy 29 (10): 572–573

Dvir Z 1995 Isokinetics: muscle testing, interpretation, and clinical application. Churchill Livingstone, Edinburgh

Dvir Z 1997 Grade 4 in manual muscle testing: the problem with submaximal strength assessment. Clinical Rehabilitation 11: 36–41

Eastlack M, Axe M, Snyder-Mackler L 1999 Laxity, instability, and functional outcome after ACL injury: copers versus noncopers. Medicine and Science in Sports and Exercise 31 (2): 210–215

Fonseca S, Magee D, Wessel J, Reid D 1992 Validation of a performance test for outcome evaluation of knee function. Clinical Journal of Sports Medicine 2 (4): 251–256

Gauffin H, Ekstrand J, Arnesson L, Tropp H 1989 Vertical jump performance in soccer players: a comparative study of two training regimes. Journal of Human Movement Studies 16: 215–224

Gauffin H, Pettersson G, Tegner Y, Tropp H 1990 Function testing in patients with old rupture of the anterior cruciate ligament. International Journal of Sports Medicine 11 (1): 73–77

Goh S, Boyle J 1997 Self-evaluation and functional testing two to four years post-ACL reconstruction. Australian Journal of Physiotherapy 43 (4): 255–262

Gould A 1994 The issue of measurement validity in health-care research. British Journal of Therapy and Rehabilitation 1 (2): 99–103

Greenberger H, Paterno M 1994a Comparison of an isokinetic strength test and a functional performance test in the assessment of lower extremity function (Abstract). Journal of Orthopaedic and Sports Physical Therapy 19 (1): 61

Greenberger H, Paterno M 1994b The test–retest reliability of a one legged hop for distance in healthy young adults (Abstract). Journal of Orthopaedic and Sports Physical Therapy 19 (1): 62

Greenberger H, Paterno M 1995 Relationship of knee extensor strength and hopping test performance in the assessment of lower extremity function. Journal of Orthopaedic and Sports Physical Therapy 22 (5): 202–206

Greenfield M, Kuhn J, Wojtys E 1996 A statistics primer: *P* Values – probability and clinical significance. American Journal of Sports Medicine 24 (6): 863–865

Greenfield M, Kuhn J, Wojtys E 1998a A statistics primer: correlation and regression analysis. American Journal of Sports Medicine 26 (2): 338–343

Greenfield M, Kuhn J, Wojtys E 1998b A statistics primer: validity and reliability. American Journal of Sports Medicine 26 (3): 483–485

Guadagnoli M, Kleiner D, Holcomb W, Miller M 1998 The assessment of leg dominance by motor function, proprioception, and strength (Abstract). Journal of Athletic Training 33 (2) Supplement: S23

Harrison E, Duenkel N, Dunlop R, Russell G 1994 Evaluation of single-leg standing following anterior cruciate ligament surgery and rehabilitation. Physical Therapy 74 (3): 245–252

Hertel J, Denegar C, Johnson P, Hale S, Buckley W 1999 Reliability of the cybex reactor in the assessment of an agility task. Journal of Sport Rehabilitation 8 (1): 24–31

Heyward V 1998 Advanced fitness assessment and exercise prescription, 3rd edn. Human Kinetics, Illinois

Hoffman M, Schrader J, Applegate T, Koceja D 1998 Unilateral postural control of the functionally dominant and nondominant extremities of healthy subjects. Journal of Athletic Training 33 (4): 319–322

Hooper D, Morrissey M, Drechsler W, King J, McAuliffe T, Bucknill T 1998 Effects of open and closed kinetic chain exercise following ACL reconstruction. In: Matsuzaki Y, Nakamura T, Eiichi T (eds). Abstracts of the Third World Congress of Biomechanics. Sapporo, Japan pp 383

Hu H, Whitney S, Irrgang J, Janosky J 1992 Test–retest reliability of the one legged vertical jump test and the one legged standing hop test (Abstract). Journal of Orthopaedic and Sports Physical Therapy 15 (1): 51

Hubley C, Wells R 1983 A work-energy approach to determine individual joint contributions to vertical jump performance. European Journal of Applied Physiology 50: 247–254

Johnson B, Nelson J 1979 Practical measurements for evaluation in physical education, 3rd edn. Burgess Publishing Company, Minnesota

Jones L 1991 The standardized test. Clinical Rehabilitation 5: 177–180

Juris P, Phillips E, Dalpe C, Edwards C, Gotlin R, Kane D 1997 A dynamic test of lower extremity function following anterior cruciate ligament reconstruction and rehabilitation. Journal of Orthopaedic and Sports Physical Therapy 26 (4): 184–191

Jurist K, Otis J 1985 Anteroposterior tibiofemoral displacements during isometric extension efforts. American Journal of Sports Medicine 13 (4): 254–258

Kannus P 1994 Isokinetic evaluation of muscular performance: implications for muscle testing and rehabilitation. International Journal of Sports Medicine 15(Supplement 1): S11–S18

Keskula D, Duncan J, Davis V, Finley P 1996 Functional outcome measures for knee dysfunction assessment. Journal of Athletic Training 31 (2): 105–110

Kramer J, Nusca D, Fowler P, Webster-Bogaert S 1992 Test–retest reliability of the one leg hop test following ACL reconstruction. Clinical Journal of Sport Medicine 2: 240–243

Kraemer W, Triplett N, Fry A, Koziris L, Bauer J, Lynch J, McConnell T, Newton R, Gordon S, Nelson R, Knuttgen

H 1995 An in-depth sports medicine profile of women college tennis players. Journal of Sport Rehabilitation 4 (2): 79–98

Krebs D 1984 Intraclass correlation coefficients: use and calculation. Physical Therapy 64: 1581–1589

Krebs D 1986 Declare your ICC type. Physical Therapy 66: 1431

Krebs D 1987 Measurement theory. Physical Therapy 67: 1834–1839

Lamb R 1985 Manual muscle testing. In: Rothstein J (ed). Measurement in Physical Therapy. Churchill Livingstone, New York, ch 2, 47–55

Lephart S 1994 Reestablishing proprioception, kinesthesia, joint position sense, and neuromuscular control in rehabilitation. In: Prentice W (ed). Rehabilitation Techniques in Sports Medicine, 2nd edn. Mosby, St Louis, ch 9, pp 118–137

Lephart S, Henry T 1995 Functional rehabilitation for the upper and lower extremity. Orthopedic Clinics of North America 26 (3): 579–592

Lephart S, Kocher M, Harner C, Fu F 1993 Quadriceps strength and functional capacity after anterior cruciate ligament reconstruction: patellar tendon autograft versus allograft. American Journal of Sports Medicine 21 (5): 738–743

Lephart S, Perrin D, Fu F, Gieck J, Gomez W, Irrgang J, McCue F, Weltman A 1988 Functional assessment of the anterior cruciate insufficient knee (Abstract). Medicine and Science in Sports and Exercise 20 (2) Supplement: S37

Lephart S, Perrin D, Fu F, Gieck J, McCue F, Irrgang J 1992 Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament insufficient athlete. Journal of Orthopaedic and Sports Physical Therapy 16 (4): 174–181

Lephart S, Perrin D, Fu F, Minger K 1991 Functional performance tests for the anterior cruciate ligament insufficient athlete. Journal of Athletic Training 26: 44–50

Lephart S, Perrin D, Minger K, Fu F, Gieck J 1989 Sport specific functional performance tests for the ACL insufficient athlete (Abstract). Journal of Athletic Training 24 (2): 119

Locke A, Sitler M, Aland C, Kimura I 1997 Long-term use of a softshell prophylactic ankle stabilizer on speed, agility, and vertical jump performance. Journal of Sport Rehabilitation 6 (3): 235–245

Luhtanen P, Komi P 1978 Segmental contribution to forces in vertical jumping. European Journal of Applied Physiology 38: 181–188

MacDonald P, Hedden D, Pacin O, Sutherland K 1996 Proprioception in anterior cruciate ligament deficient and reconstructed knees. American Journal of Sports Medicine 24 (6): 774–778

Mangine R, Noyes F, DeMaio M 1992 Minimal protection program: advanced weight bearing and range of motion after ACL reconstruction – weeks 1 to 5. Orthopedics 15 (4): 504–515

Mayhew T, Rothstein J 1985 Measurement of muscle performance with instruments. In: Rothstein J (ed). Measurement in Physical Therapy. Churchill Livingstone, New York, ch 3, pp 57–102

Miller R, Carr A 1993 The knee. In: Pynsent P, Fairbank J, Carr A (eds). Outcome Measures in Orthopaedics. Butterworth Heinemann, Oxford, ch 11, pp 229–241

Morrissey M 1994 . Range of Motion and Velocity in Resistance Training. Doctor of Science Dissertation. Sargent College of Allied Health Professions. Boston University. Boston, USA

Natri A, Jarvinen M, Latvala K, Kannus P 1996 Isokinetic muscle performance after anterior cruciate ligament surgery: long-term results and outcome predicting factors after primary surgery and late-phase reconstruction. International Journal of Sports Medicine 17 (3): 223–228

Neeb T, Aufdemkampe G, Wagener J, Mastenbroek L 1997 Assessing anterior cruciate ligament injuries: the association and differential value of questionnaires, clinical tests, and functional tests. Journal of Orthopaedic and Sports Physical Therapy 26 (6): 324–331

Noyes F, Barber S, Mangine R 1991 Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. American Journal of Sports Medicine 19 (5): 513–518

Ostenberg A, Roos E, Ekdahl C, Roos H 1998 Isokinetic knee extensor strength and functional performance in healthy female soccer players. Scandinavian Journal of Medicine and Science in Sports 8: 257–264

Paterno M, Greenberger H 1996 The test–retest reliability of a one legged hop for distance in young adults with and without ACL reconstruction. Isokinetics and Exercise Science 6: 1–6

Perrin D 1993 Isokinetic Exercise and Assessment. Human Kinetics, Illinois

Petschnig R, Baron R, Albrecht M 1998 The relationship between isokinetic quadriceps strength test and hop tests for distance and one legged vertical jump test following anterior cruciate ligament reconstruction. Journal of Orthopaedic and Sports Physical Therapy 28 (1): 23–31

Pincivero D, Lephart S, Karunakara R 1997 Relation between open and closed kinematic chain assessment of knee strength and functional performance. Clinical Journal of Sport Medicine 7 (1): 11–16

Portney L, Watkins M 1993 Foundations of Clinical Research: Applications to Practice. Appleton & Lange, Connecticut

Publications Advisory Committee 1992 Units of measurement and terminology. In: Komi P (ed). Strength and Power in Sport. Blackwell Scientific Publications, Oxford, pp xi

Risberg M, Ekeland A 1994 Assessment of functional tests after anterior cruciate ligament surgery. Journal of Orthopaedic and Sports Physical Therapy 19 (4): 212–217

Risberg M, Holm I, Ekeland A 1995 Reliability of functional knee tests in normal athletes. Scandinavian Journal of Medicine and Science in Sports 5: 24–28

Robertson D, Fleming D 1987 Kinetics of standing broad and vertical jumping. Canadian Journal of Sports Science 12 (1): 19–23

Rothstein J 1985 Measurement and clinical practice: theory and application.. In: Rothstein J (ed). Measurement in

Physical Therapy. Churchill Livingstone, New York, ch 1, pp 1–46
Rothstein J 1993 Reliability and validity: implications for research. In: Bork C (ed). Research in Physical Therapy. JB Lippincott Company, Philadelphia, ch 2, pp 18–36
Rudolph K, Axe M, Snyder-Mackler L 1999 Implications of dynamic stability after ACL injury: who can hop and who cannot (Abstract). Journal of Orthopaedic and Sports Physical Therapy 29 (1): A45–A46
Sachs R, Daniel D, Stone M, Garfein R 1989 Patellofemoral problems after anterior cruciate ligament reconstruction. American Journal of Sports Medicine 17 (6): 760–765
Sapega A 1990 Muscle performance evaluation in orthopaedic practice. Journal of Bone and Joint Surgery 72A (10): 1562–1574
Sekiya I, Muneta T, Ogiuchi T, Yagishita K, Yamamoto H 1998 Significance of the single leg hop test to the anterior cruciate ligament reconstructed knee in relation to muscle strength and anterior laxity. American Journal of Sports Medicine 26 (3): 384–388
Shelbourne K, Nitz P 1990 Accelerated rehabilitation after anterior cruciate ligament reconstruction. American Journal of Sports Medicine 18 (3): 292–299
Shrout P, Fleiss J 1979 Intraclass correlations: uses in assessing rater reliability. Psychological Bulletin 86 (2): 420–428
Szczerba J, Perrin D, Kaminski T 1995 Assessment of lower extremity dominance via strength and balance measurements (Abstract). Journal of Athletic Training 30(Supplement): S42
Task force on standards for measurement in physical therapy 1991 Standards for tests and measurements in physical therapy practice. Physical Therapy 71: 589–622
Tegner Y, Lysholm J 1985 Derotation brace and knee function in patients with anterior cruciate ligament tears. Arthroscopy 1 (4): 264–267
Tegner Y, Lysholm J, Lysholm M, Gillquist J 1986 A performance test to monitor rehabilitation and evaluate anterior cruciate ligament injuries. American Journal of Sports Medicine 14 (2): 156–159
Thomas M, Fiatarone M, Fielding R 1996 Leg power in young women: relationship to body composition, strength, and function. Medicine and Science in Sports and Exercise 28 (10): 1321–1326
Tippett S, Voight M 1995 Functional Progressions for Sport Rehabilitation. Human Kinetics, Illinois
Vincent W 1995 Statistics in Kinesiology. Human Kinetics, Illinois
Voight M, Draovitch P, Tippett S 1995 Plyometrics. In: Albert M (ed). Eccentric Muscle Training in Sports and Orthopedics, 2nd edn. Churchill Livingstone, New York, ch 6, pp 61–88
Voight M, Tippett S 1994 Plyometric exercise in rehabilitation. In: Prentice W (ed). Rehabilitation Techniques in Sports Medicine, 2nd edn. Mosby, St Louis, ch 6, pp 88–97
Wiklander J, Lysholm J 1987 Simple test for surveying muscle strength and muscle stiffness in sportsmen. International Journal of Sports Medicine 8 (1): 50–54
Wilk K, Andrews J 1992 Current concepts in the treatment of anterior cruciate ligament disruption. Journal of Orthopaedic and Sports Physical Therapy 15 (6): 279–293
Wilk K, Andrews J 1993 The effects of pad placement and angular velocity on tibial displacement during isokinetic exercise. Journal of Orthopaedic and Sports Physical Therapy 17 (1): 24–30
Wilk K, Romaniello W, Soscia S, Arrigo C, Andrews J 1994 The relationship between subjective knee scores, isokinetic testing, and functional testing in the ACL-reconstructed knee. Journal of Orthopaedic and Sports Physical Therapy 20 (2): 60–73
Wojtys E, Greenfield M, Kuhn J 1996 A statistics primer: statistical terminology – Part 2. American Journal of Sports Medicine 24 (4): 564–565
Wojtys E, Huston L 1994 Neuromuscular performance in normal and anterior cruciate ligament deficient lower extremities. American Journal of Sports Medicine 22 (1): 89–104
Worrell T, Borchert B, Erner K, Fritz J, Leerar P 1993 Effect of a lateral step-up exercise protocol on quadriceps and lower extremity performance. Journal of Orthopaedic and Sports Physical Therapy 18 (6): 646–653