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Lunge performance and its determinants

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For activities such as squash, badminton and fencing, the ability to quickly complete a lunge and return to the start or move off in another direction is critical for success. Determining which strength qualities are important predictors of lunge performance was the focus of this study. Thirty-one male athletes performed: (1) a unilateral maximal squat (one-repetition maximum, 1-RM) and unilateral jump squat (50% 1-RM) on an instrumented supine squat machine, and (2) a forward lunge while attached to a linear transducer. We performed stepwise multiple regression analysis with lunge performance as the dependent variable and various strength, flexibility and anthropometric measures as the independent variables. From the many strength and power measures calculated, time to peak force was the best single predictor of lunge performance, which accounted for 55% of the explained variance. The best three-variable model for predicting lunge performance accounted for 76–85% of the explained variance. The models differed, however, according to whether lunge performance was expressed relative to body mass (time to peak force, mean power and relative strength = 76%) or taken as an absolute value (time to peak force, leg length and flexibility = 85%). We conclude that one to two trials were reliable for strength diagnosis and that one strength measure cannot accurately explain functional performance because other factors, such as body mass, flexibility and leg length, have diverse effects on the statistical models.

Keywords: concentric, power, rate of force development, strength.

Introduction

Strength and power are important aspects of fitness, sport and everyday activity. However, much debate remains as to how these two qualities should be assessed. Much of the debate originates from the definition of strength and power and the different terminology used across laboratories. Sale (1991) defined strength as the force exerted under a given set of conditions during a maximal voluntary contraction (MVC). Sale continued to define power as the rate at which mechanical work is performed under a specified set of conditions, or the product of force and velocity. Both definitions imply that strength and power are defined by conditions such as velocity, contraction type, posture and movement pattern specificity. That is, strength for one task may not imply strength for another. An associated problem with this is that strength and power are quite often measured in contexts dissimilar to the environment in which functional strength and power are needed. Consequently, much research has investigated development of force and power and the relationship of these measures to functional performance (Wiklander and Lysholm, 1987; Sachs *et al.*, 1989; Anderson and Pandy, 1991; Wilson *et al.*, 1995; Young *et al.*, 1995; Murphy and Wilson, 1996; Jameson *et al.*, 1997).

The great diversity in the approaches and terminology used for studying strength and power do not make for easy understanding or comparisons across research. This diversity is readily apparent when studying rate of force development. For example, starting strength (force at 30 ms), initial rate of force development and S-gradient for the most part measure a similar construct but use different portions of the force–time curve (Schmidtbleicher, 1985; Tidow, 1990; Zatsiorsky, 1995). Zatsiorsky (1995) used terms such as the index of explosive strength, reactivity coefficient, S-gradient and A-gradient to describe rate of force development. The index of explosive strength refers to the ability to exert maximal forces in minimal time. The reactivity coefficient expresses the index of explosive strength relative to body mass and is reportedly highly correlated with jumping performance, particularly with body velocity at take-off (Zatsiorsky, 1995). The S-gradient characterizes the rate of force development at the

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beginning phase of muscular effort, whereas the A-gradient quantifies rate of force development in the late stages of muscular effort (Zatsiorsky, 1995). Apart from these descriptions and the formulae themselves, Zatsiorsky's treatise of these strength qualities was vague and their relationships to other strength qualities or functional performance were not detailed. This study sought a better understanding of these force–time measurements.

Some activities, such as sprinting, jumping and throwing, require force to be produced within 100–250 ms and have been classified as fast stretch–shorten cycle (SSC) activities (<250 ms) (Tidow, 1990; Schmidtbleicher, 1992). It has been proposed that, in such events, the rate of force development may be the most important physical capacity (Schmidtbleicher, 1992). Some research supports such a proposition. For example, Wilson *et al.* (1995) investigated the relationship between sprinting performance and a series of isometric, concentric and SSC rate of force development tests performed in an upright squat position. Of the 20 force–time variables generated using a modified Smith machine over a force platform, the concentric force at 30 ms was the only measure significantly correlated with sprint performance ($r=-0.616$) and able to effectively discriminate between good and poor performers. Adopting a similar method to Wilson *et al.* (1995), Young *et al.* (1995) assessed vertical jumping movements using purely concentric, SSC and isometric contractions performed over a force platform and found that concentric strength measures were the best predictors of sprint performance. For starting performance (2.5 m time), concentric peak force relative to body mass was found to be the best single predictor ($r=0.86$). The best single correlate of maximum running speed was the force applied at 100 ms (relative to body mass) during a concentric jump ($r=0.80$). It would appear from the results of these investigations that isoinertial (performed with a constant gravitational load, e.g. weightlifting tasks; Abernethy *et al.*, 1995) measures of concentric (no countermovement) strength qualities are better indicators of functional performance than other contraction types. Few studies have examined the strength qualities important in producing forceful slow SSC motion. However, Schmidtbleicher (1992) did suggest that maximal strength is more important for movements of 250 ms or longer.

For activities such as squash, badminton and fencing, sprint performance is of little relevance and other aspects of athletic performance are more important. The ability to quickly complete a lunge and return to the start or move off in another direction is critical for success in such sports. Of particular interest to the present study was the relationship between strength qualities and lunge ability. To our knowledge, no research has examined the relationship between strength qualities and this type of activity. In the absence of research investigating lunge performance, it may be assumed that the strength qualities important in predicting sprint performance may also be related to lunge performance. However, we hypothesized that, because the lunge is a relatively slow SSC activity compared with the foot contact times of sprinting, other strength qualities (such as maximal strength) may be more important.

The main aim of this study was to determine which strength qualities are important predictors of lunge performance. Such information may provide information for talent identification, injury prevention, rehabilitation or development of this functional task. A secondary aim was to provide a better understanding of the force–time measurements used by Zatsiorsky (1995) to measure fast force production.

Methods

Participants

Thirty-one males volunteered to participate in the present study. The participants were involved in a wide variety of sports that predominantly involved the lower body. Descriptive statistics of the participants are presented in Table 1. The Auckland University of Technology Ethics Committee approved the study and each participant provided written informed consent before taking part in the research.

Equipment

Supine squat machine

The supine squat machine was custom-built (Fitness Works, Auckland, NZ) and used a 300 kg pin-loaded weight stack to provide resistance. A linear transducer (P-80A, Unimeasure, Oregon; average sensitivity 0.499 $\mathrm{mV{\cdot}V^{-1}{\cdot}mm^{-1}}$, linearity 0.05% full scale) was attached to the weight stack and measured vertical displacement relative to the ground with an accuracy of 0.1 cm. The variables of interest in this study were calculated from the mass-displacement characteristics of this stack. The data were sampled at 200 Hz by a computer-based (Macintosh G4 Computer, Cupertino, CA) data acquisition and analysis program (Superscope Version 3, GW Instruments, Boston, MA). The machine was designed to allow participants to perform maximal squats or explosive squat jumps with the back rigidly supported, thus minimizing the risk associated with such exercises in an upright position (see Fig. 1).

Table 1. Physical characteristics of the participants and performance of the supine squat and lunge (mean ± *s*)

Physical characteristics	
Age (years)	23.1 ± 4.8
Height (m)	1.76 ± 0.1
Mass (kg)	76.3 ± 11.6
Leg length (cm)	83.9 ± 5.2
Flexibility (cm)	171 ± 16.5
Lunge performance	
Maximum concentric velocity (m·s^{-1})	1.64 ± 0.247
Maximum eccentric velocity (m·s^{-1})	1.68 ± 0.144
Supine squat performance	
Duration of contraction (s)	0.981 ± 0.092
Average velocity (m·s^{-1})	0.508 ± 0.066
Peak velocity (m·s^{-1})	1.12 ± 0.14
Average force (N)	715 ± 174
Peak force (N)	945 ± 233
Time to peak force (s)	0.471 ± 0.073
50% force (N)	120 ± 35.9
Time to 50% force (s)	0.216 ± 0.070
Impulse at 100 ms (N·s^{-1})	72.5 ± 17.3
Mean power (W)	364 ± 96.8
Peak power (W)	932 ± 258
Maximal strength (kg)	127 ± 35.9
Relative strength (kg·body mass^{-1})	1.65 ± 0.32

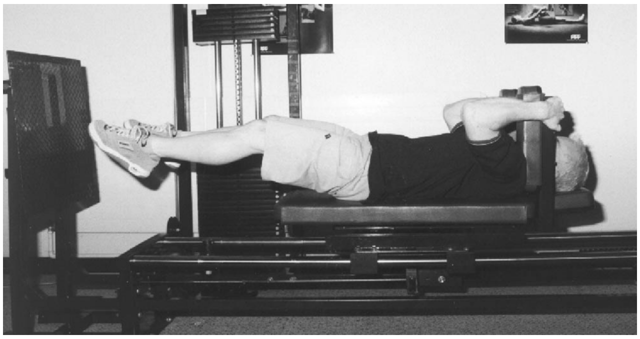

Fig. 1. Isoinertial supine squat machine.

Linear transducer

A linear transducer (HX-PA-2000, Unimeasure, Oregon; average sensitivity 0.019 mV·V^{-1}·mm^{-1}, linearity 0.05% full scale), which was supported on a tripod and attached to the trunk of the participant, measured horizontal displacement during lunge performance. The data were sampled at 200 Hz by a computer-based data acquisition and analysis program. However, the temporal and velocity characteristics of the lunge movement were the only variables of interest using this device. The wire from the transducer was spring loaded and allowed measurement during both the forward and return phases of the lunge.

Test protocol

For most participants, testing was performed on two separate days at similar times, with at least 2 days but no more than 7 days between sessions. To establish the reliability of the procedures and variables of interest, 13 participants agreed to repeat the assessment procedures 7–10 days after the first assessment.

To improve specificity, we assessed unilateral strength and power, as most athletic activities, including the lunge, involve unilateral propulsion. Each session was preceded by a standardized warm-up involving multidirectional running and static stretches. The first session involved familiarization with the performance of the test items and measurement of each participant's leg length, flexibility and maximal strength. Mean leg length (right side) was measured from the midpoint of the greater trochanter to the midpoint of the lateral malleolus. Flexibility was measured as the linear distance between the lateral malleolus of each leg during a split in the frontal plane. The frontal plane was used as a pilot test of flexibility in the sagittal plane found the variation and reliability of these measurements to be unacceptable, as measured by the coefficient of variation and intraclass correlation coefficient, respectively. Maximal strength was assessed using the supine squat machine and measured as the load (kg) that each participant could lift for one repetition (1-RM) with his preferred leg. Foot position was standardized and each participant's knee angle was set at 90° using a goniometer aligned to the lateral malleolus, lateral epicondyle of the knee and greater trochanter of the left leg. A knee angle of 90° was selected as it had greater specificity to the angles used in lunge performance (Klinger and Adrian, 1983). The participants began from a flexed position with the plates at rest and extended concentrically for each trial until their 1-RM was established.

The second session began with the standardized warm-up, after which lunge performance was assessed. Data relating to the displacement of the participant during the lunge movement were provided by the linear transducer, which was attached to the participant via a belt, strapped to the trunk. The movement involved a forward lunge (1.5 times leg length) to a marker and return to the starting position as rapidly as possible. Three trials were performed on the preferred leg.

After the lunge test, unilateral power was assessed using the instrumented supine squat machine. The start position of the movement was as described previously, but the participants were instructed to move the sled load (50% 1-RM) as 'explosively' as possible (see Fig. 1). Such jump squat motion closely simulates the velocity and acceleration profiles and, therefore, contraction dynamics associated with functional performance (Newton *et al.*, 1996). Once again, three trials were performed on the preferred leg.

Data collection and analysis

The displacement–time data from the supine squat machine and linear transducer were filtered using a low-pass Hamming filter with a cut-off frequency of 10 Hz (Cronin *et al.*, 2001). The filtered data were then differentiated using a finite difference algorithm to determine velocity and acceleration data, from which it was possible to calculate the impulse at 100 ms, force, power and temporal characteristics of the movement (see Table 1). Peak force, time to peak force, 50% force and body mass were the variables used to calculate measures of explosive strength according to the formulae of Zatsiorsky (1995):

index of explosive strength = peak force/time to peak force
reactivity coefficient = peak force/(time to peak force × body mass)
start gradient = 50% force/time to 50% force
acceleration gradient =

$$\frac{\text{50\% force}}{\text{(time to peak force} - \text{time to 50\% force)}}$$

Of the variables measured by the supine squat, maximal strength and relative strength were derived from the maximal strength assessment, whereas all other kinematic and kinetic measures were derived from the 50% 1-RM squat jump assessment.

The measurement of force as described here has been verified by comparison of the linear transducer data with data gathered simultaneously from an accelerometer and a force platform across movement types (concentric-only and rebound bench presses – squat, countermovement and drop jumps), loads (40–80% 1-RM) and sampling frequencies (200–1000 Hz). The data from the linear transducer were shown to be reliable (intraclass correlation coefficient = 0.92–0.98 for measures of mean and peak force) and valid across these conditions. The reliability of the procedures has been reported previously (Cronin *et al.*, 2001).

Statistical analysis

To establish the reliability of the human performance measures examined in this study, two variables were selected for analysis. As it has been shown that mean power is the most sensitive parameter among all the mechanical variables, because it is the product of the force (acceleration) and velocity data (Bosco *et al.*, 1999), it was used for reliability analysis. Similarly, maximum concentric velocity was used for reliability analysis of the lunge performance. Maximum concentric velocity was chosen as the dependent variable, as the time to complete the lunge movement was found to be related to the velocity of movement ($r = 0.954$). We chose concentric velocity, rather than eccentric velocity, as concentric average and peak velocities were measured using the isoinertial squat machine. Furthermore, using velocity as the dependent variable allowed comparisons with other research that studied lunge performance (Klinger and Adrian, 1983). The reliability of the assessment of these two human performance variables was assessed using two different statistical techniques. Intraclass correlation coefficients were calculated to determine inter-trial and test–retest reliability, and coefficients of variation (CV) were used to quantify the variability within trials (CV = *s*/mean).

An intercorrelation matrix was performed between the traditional strength and power measures and those described by Zatsiorsky (1995) to determine their interrelationships. The variables included traditional strength (mean and peak force) and power measures (mean and peak power), as well as measures of explosive strength (impulse at 100 ms, index of explosive strength, S-gradient, A-gradient and reactivity coefficient).

To assess the relationships among the independent and dependent variables, we used stepwise multiple regression analysis with lunge performance as the dependent variable and various strength, flexibility and anthropometric measures as the independent variables. Our aim was to identify those qualities that were important in optimizing lunge performance. Subsequent analysis involved the stepping in and out of those independent variables that provided the greatest value for the multiple correlation coefficient. The best single-, double- and three-predictor models of each dependent variable were presented as correlation coefficients (r) and as coefficients of determination (R^2). The sample size ($n = 31$) was not considered large enough to provide the statistical power to justify more than three predictors. Significance was set at $P < 0.05$ for all statistical models.

Results

The parameters used to describe the attributes of the participants and to characterize lunge and supine squat performance are presented in Table 1. The maximum velocities recorded during the concentric and eccentric phases of the lunge were similar at 1.64 and 1.68 m·s^{-1}, respectively. The peak velocity recorded during the 50% 1-RM squat jump was considerably slower (1.12 m·s^{-1}) than that recorded during the lunge.

Unilateral maximal squat strength was 127.1 kg, which equated to the participants lifting 1.65 kg per kilogram of body mass. The kinematic and kinetic characteristics of the supine jump squat (50% 1-RM) are also presented in Table 1.

The mean, standard deviation and reliability coefficients for the lunge and supine squat performance are presented in Table 2. The coefficients of variation were 3.6% (mean power) and 5.8% (maximum concentric velocity). The intraclass correlation coefficients within a test session and between the two test sessions are also presented in Table 2. Intra-trial correlation coefficients were calculated by comparing the first trial of each variable to the mean of three trials. As can be observed from Table 2, both maximum concentric velocity and mean power demonstrated significant intraclass correlation coefficients of 0.936 and 0.988, respectively. These findings indicate that a single trial may be as effective as multiple trials when measuring the dependent and independent variables as described above. Test–retest reliability compared the mean of three trials between test sessions. The measurement of velocity and power was found to be consistent between sessions, with intraclass correlation coefficients of 0.863 and 0.958, respectively.

The intercorrelation matrix revealed that all strength measures were significantly related to one another (see Table 3). The magnitude of the correlations between the traditional measures of strength and power were especially high ($r = 0.833$–0.989). However, the magnitude of the correlations between these traditional measures and Zatsiorsky's measures were much lower ($r = 0.430$–0.857). This represents a shared variance of 18.5–72.3%. Of Zatsiorsky's measures, the index of explosive strength was most highly correlated with the other three measures (reactivity coefficient, S-gradient and A-gradient), with all correlations $\geqslant 0.80$. The relationship between the S-gradient and A-gradient was significant ($r = 0.554$), but the S-gradient only accounted for 30.6% of the variance associated with the A-gradient.

Table 4 shows the variables that were significantly related to the maximum concentric velocity achieved during lunge performance and the best single-, two-

Table 2. Maximum concentric velocity achieved during a lunge and mean power output during a supine concentric-only squat (mean ± *s*)

Variable	Mean ± *s*	Intra-trial ICC	CV (%)	Test–retest ICC
Lunge performance				
Maximum concentric velocity ($m \cdot s^{-1}$)	1.62 ± 0.207	0.936 (0.001)	5.8	0.863 (0.001)
Supine squat performance				
Mean power (W)	364 ± 96.8	0.988 (0.001)	3.6	0.958 (0.001)

Note: Intraclass correlation coefficients (ICC) for intra-trial reliability (first trial compared with the mean of three trials) and test–retest reliability (mean of three trials compared across separate test occasions) are also presented. The coefficient of variation (CV) was calculated between trials according to the formula *s*/mean × 100. *P*-values are reported in parentheses.

Table 3. Intercorrelation matrix between traditional strength and power measures and Zatsiorsky's measures of explosive strength

	MP	PP	MF	PF	I_{100}	MS	IES	RC	SG	AG
MP										
PP	0.989									
MF	0.876	0.848								
PF	0.916	0.903	0.986							
I_{100}	0.887	0.858	0.998	0.985						
MS	0.848	0.833	0.935	0.940	0.935					
IES	0.753	0.743	0.799	0.857	0.795	0.805				
RC	0.430	0.447	0.551	0.608	0.539	0.561	0.841			
SG	0.761	0.735	0.620	0.689	0.534	0.687	0.848	0.684		
AG	0.541	0.597	0.524	0.633	0.511	0.570	0.801	0.763	0.554	

Abbreviations: MP = mean power, PP = peak power, MF = mean force, PF = peak force, I_{100} = impulse at 100 ms, MS = maximal strength, IES = index of explosive strength, RC = reactivity coefficient, SG = starting gradient, AG = acceleration gradient.
Note: All correlations are statistically significant at $P < 0.05$.

and three-predictor models for lunge performance. For both lunge models, the time to peak force was the best single predictor of lunge performance ($R^2 = -0.61$ to -0.74) but accounted for less than 55% of the explained variance. The explosive strength measures as described by Zatsiorsky (1995) were moderately correlated with lunge performance.

The statistical models used to predict lunge performance were different if the dependent variable was expressed relative to body mass. The best three-predictor model of maximum concentric velocity included leg length and flexibility, accounting for 85% of the common variance associated with lunge performance. However, when expressed relative to body mass, mean power and relative strength became the important predictors of lunge performance in combination with time to peak force. This model accounted for 76% of the common variance associated with maximum concentric velocity while lunging.

Discussion

Reliability

Although there are no preset standards for acceptable reliability measures, Walmsley and Amell (1996) suggested that intraclass correlation coefficients above 0.75 may be considered reliable and this index should be at least 0.90 for most clinical applications. A coefficient of variation of 10% or less has been chosen arbitrarily by some scientists, but the merits of this value have been the source of conjecture (Atkinson and Nevill, 1998). Nonetheless, inter-trial reliability (Table 2) was acceptable, since the intraclass correlation coefficients (ICCs) were above 0.90 and the coefficients of variation were less than 6.0%. It would appear that the procedures and equipment used to measure the dependent and independent variables were stable between trials and similar to other research testing new devices and procedures. For example, testing the reliability of an isokinetic squat device, Wilson *et al.* (1997) reported inter-trial ICCs of 0.89–0.96 and coefficients of variation of 3.1–8.7% for a concentric and stretch–shorten cycle (SSC) squat. Lower correlation's were noted by Rahmani *et al.* (2000), who reported intraclass correlation coefficients of 0.57–0.91 for peak force, peak velocity and peak power during a half squat on an isoinertial squat rack instrumented with an optical encoder.

Analysis of between-trial consistency (inter-trial ICC and coefficient of variation) indicated that the information gained from multiple trials does not differ greatly from a single trial. Similar findings across different paradigms have been reported elsewhere (Dowling and Vamos, 1993; Topp and Mikesky, 1994). Topp and Mikesky (1994) found that a single trial was as effective as multiple trials when measuring isometric dorsi/plantar flexion using a hand-held dynamometer. Dowling and Vamos (1993) used only one trial in their study of the kinetic and temporal characteristics of vertical

Table 4. Significant correlation coefficients (R) and subsequent coefficients of determination (R^2) for maximum concentric velocity of the lunge (LUN) and the lunge expressed relative to body mass (LUN/M) (a description of the best single-, two- and three-predictor statistical models for lunge performance as calculated by stepwise multiple regression is also presented)

	Dependent variables			
	LUN		LUN/M	
Independent variables	R (P-value)	R^2	R (P-value)	R^2
Supine squat machine				
Time to peak force (TPF)	−0.74 (0.01)	0.54	−0.61 (0.03)	0.37
Time to 50% force (TFF)	−0.57 (0.05)	0.32		
Index of explosive strength (IES)	0.62 (0.03)	0.38		
Reactivity coefficient (RC)	0.61 (0.03)	0.37		
S-gradient (SG)	0.69 (0.01)	0.48		
A-gradient (AG)	0.59 (0.04)	0.34		

Best predictors	LUN	R	R^2	LUN/M	R	R^2
Single predictor	TPF	0.74	0.54	TPF	0.61	0.37
Two predictors	TPF, LL	0.88	0.77	TPF, MP	0.81	0.66
Three predictors	TPF, LL, FL	0.92	0.85	TPF, MP, RS	0.87	0.76

jump performance, as there was very little variability within one participant's performance relative to the variability between participants. The practical application of such findings for strength assessment is that, in cases in which many participants are being assessed and time is a constraint, only one to two trials are needed to gather reliable information. Furthermore, in research paradigms where many conditions are being compared, order, fatigue and motivation effects may confound results. In such circumstances, just a few trials would appear to be acceptable to gather reliable information.

Test–retest intraclass correlation coefficients were high for the variables investigated. It would appear that the instrumented supine squat machine and linear transducer can reliably measure the variables detailed in Table 2. The intraclass correlation coefficients ($r = 0.863$–0.988) compared favourably to those cited in other research assessing new dynamometers or test procedures (Topp and Mikesky, 1994; Walshe *et al.*, 1996). Walshe *et al.* (1996) reported a test–retest intraclass correlation coefficient of 0.94 and a coefficient of variation of 8% for their tests of lower-body musculotendinous stiffness. In assessing ankle dorsi/plantar flexion strength using isometric and isokinetic assessment, Topp and Mikesky (1994) reported intertrial ICCs of 0.92–0.97 and test–retest reliability ICCs of 0.74–0.93.

Strength measures

A secondary aim of this study was to provide a better understanding of the force–time measurements used by Zatsiorsky (1995) to measure fast force production. Of Zatsiorsky's measures, the index of explosive strength was most highly correlated with the other three measures (the reactivity coefficient, S-gradient and A-gradient), with all correlations $\geqslant 0.80$. If one measure were to be used to denote the force–time (explosive strength) characteristics of a particular movement, this would be the variable of choice. It not only explains most of the variance associated with the reactivity coefficient (70.5%), but also explains much of the variance associated with early (S-gradient = 71.9%) and late (A-gradient = 64.0%) force development. The S-gradient and A-gradient appear to measure different strength qualities ($r = 0.554$), as the S-gradient only accounted for 30.6% of the variance associated with the A-gradient. This was expected, as these calculations were based on different portions of the force–time curve. The relationship between these measures and initial rate of force development and maximal rate of force development warrants further investigation.

The relationship between these measures of explosive strength and more traditional measures of impulse, force and power suggest that Zatsiorsky's strength qualities, for the most part, measure different strength qualities to more traditional measures. In particular, the reactivity coefficient ($r = 0.430$–0.608), S-gradient ($r = 0.534$–0.761) and A-gradient ($r = 0.511$–0.633) have less of their variance explained by impulse, force and power. Which of these measures is better suited for identifying the strength and power requirements of a particular event – and hence talent identification, strength diagnosis and monitoring changes in performance of that event – requires a great deal more research of the nature reported here.

The significant predictors of lunge performance are described in Table 4. All the measures would appear to be related to some aspect of fast force production. Zatsiorsky's measures were significantly related to lunge performance, though much of the variance between the dependent variable and these strength qualities (34–48%) remains unexplained. Although explosive strength was an important predictor of performance in this task, other strength qualities or other variables not measured in this study may be of greater importance. The findings suggest that lunge performance would benefit from strength training that aimed to improve the explosive strength or rate of force development of the involved muscles. This would appear to conflict with Schmidtbleicher's (1992) suggestion that slow SSC motion (> 0.25 s) would benefit from maximal strength training, as the lunge foot contact times recorded in this research (0.354 ± 0.063 s) would be classified as slow according to Schmidtbleicher's definition. The relationship between unilateral maximal strength as assessed on the supine squat machine and lunge performance was found to be non-significant ($r = 0.242$, $P = 0.449$). Whether this was due to a lack of posture specificity during the assessment is a matter of conjecture. Nonetheless, it would appear that methods aimed at improving fast SSC ability are most suitable for improving lunge performance.

Lunge performance

Little research has focused on the correlation of strength and power indices with athletic performance. Abernethy *et al.* (1995) maintained that more research was needed, as such correlational analysis allowed the relationship between strength and power and athletic activity to be identified. This, in turn, will aid talent identification and strength diagnosis, and improve training and rehabilitation interventions. The limited research of this type was evident when investigating lunge performance, which was surprising considering the importance of lunge-type activity in many sports. Lunge performance has been investigated in fencing in terms of the kinematics and the electromyographic activity associated with the movement (Klinger and

Adrian, 1983; Hefzy *et al.*, 1997). Klinger and Adrian (1983) reported lunge velocities of 1.5–4.0 $m\cdot s^{-1}$, with an average velocity of 2.41 $m\cdot s^{-1}$. They concluded that the most experienced fencers achieved the greatest lunge velocities. The average velocity (1.62 $m\cdot s^{-1}$) recorded in the present study would indicate the relatively untrained status of the participants in terms of lunge performance.

To our knowledge, the relationship between lunge performance and various strength measures has not previously been investigated. Our results indicate that the ability to produce peak force earlier in the concentric phase on the supine squat machine was the best predictor of lunge performance. Furthermore, leg length and flexibility accounted for 85% of the common variance associated with the maximum concentric velocity achieved during lunging. The importance of producing maximum force earlier in a contraction, and hence the impact on the velocity characteristics of motion and the subsequent relation to lunge performance, intuitively makes sense. The benefits of greater leg length and flexibility to lunge performance may be attributed to biomechanical or physiological mechanisms, which are outside the scope of this discussion.

If lunge performance was expressed as a function of body mass, the best predictors of maximum concentric velocity altered to include time to peak force and two new strength measures, namely mean power and relative strength, which accounted for 76% of the common variance associated with lunge performance. The rationale for normalizing body mass to lunge performance was to note whether the mass of the participants was somehow an advantage or disadvantage to the movement. For example, it may be that a larger body mass requires greater forces to brake the body's horizontal and vertical momentum during the lunge forward. The time from the beginning of the eccentric contraction to the onset of the concentric contraction (amortization capacity) is thought to be central to exploiting the elastic properties of muscle (Bosco and Komi, 1979). As such, longer amortization phases and longer coupling times (duration of transition between eccentric and concentric contractions) might be expected, which ultimately affect the concentric velocity of a contraction. Expressing lunge performance relative to body mass did affect the predictor models. Possessing greater mean power and relative strength in combination with faster times to peak force would intuitively benefit lunge-type activity. Such findings suggest that an approach that uses traditional maximal strength training that aims at neural rather than hypertrophic adaptation, in combination with explosive strength training, may help optimize lunge performance. Such a mixed-method approach may best facilitate improvement in lunge performance, as SSC activity associated with the lunge cannot be classified as truly fast or slow SSC activity.

Most correlational studies have reported correlations of $r = 0$–0.86 between strength measurements and functional performance (Wiklander and Lysholm, 1987; Sachs *et al.*, 1989; Anderson and Pandy, 1991; Wilson *et al.*, 1995; Young *et al.*, 1995; Murphy and Wilson, 1996; Jameson *et al.*, 1997). The results of this research are no different ($r = 0.59$–0.74). However, the preoccupation of most correlational research with finding a single strength measure that best predicts some aspect of functional performance appears questionable. A true functional assessment is not possible with a single strength test because there are so many variables that affect functional performance. We have also shown that factors such as body mass, flexibility and leg length affect the performance of a specific task and, therefore, the interaction of various strength variables in predicting performance.

Conclusion

In terms of predicting lunge performance from the variables measured on the isoinertial supine squat machine, time to peak force was found to be the best single predictor. The strength measures as described by Zatsiorsky predicted lunge performance better than traditional measures. The best three-variable model for predicting lunge performance differed according to whether lunge performance was expressed relative to body mass or taken as an absolute value. We conclude that the preoccupation of correlational studies with finding the best strength predictors of functional performance is fundamentally flawed. First, one strength measure cannot adequately express or provide insight into all the mechanisms responsible for performance of a task. Second, other factors such as body mass, flexibility and leg length have diverse effects on the statistical models. Based on these results, we suggest that sports trainers, sport scientists and clinicians should not rely solely on a single strength measurement to predict performance or readiness to return to activity after injury. Rather, research needs to determine the influence of these other factors on functional performance. It may be that several factors in combination with strength measures will provide the best predictive capabilities of functional performance. The challenge, therefore, is to develop assessment batteries that provide insights into the key mechanisms responsible for the performance of a task. Such an approach would benefit exercise analysis, strength diagnosis, rehabilitation and talent identification and help monitor performance changes with greater validity and accuracy.

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