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Measurement of Resistance Exercise Force Expression

Loren Z.F. Chiu[1], Brian K. Schilling[2], Andrew C. Fry[2], and Lawrence W. Weiss[2]
[1]University of Southern California; [2]University of Memphis

Displacement-based measurement systems are becoming increasingly popular for assessment of force expression variables during resistance exercise. Typically a linear position transducer (LPT) is attached to the barbell to measure displacement and a double differentiation technique is used to determine acceleration. Force is calculated as the product of mass and acceleration. Despite the apparent utility of these devices, validity data are scarce. To determine whether LPT can accurately estimate vertical ground reaction forces, two men and four women with moderate to extensive resistance training experience performed concentric-only (CJS) and rebound (RJS) jump squats, two sessions of each type in random order. CJS or RJS were performed with 30%, 50%, and 70% one-repetition maximum parallel back squat 5 minutes following a warm-up and again after a 10-min rest. Displacement was measured via LPT and acceleration was calculated using the finite-difference technique. Force was estimated from the weight of the lifter-barbell system and propulsion force from the lifter-barbell system. Vertical ground reaction force was directly measured with a single-component force platform. Two-way random average-measure intraclass correlations (ICC) were used to assess the reliability of obtained measures and compare the measurements obtained via each method. High reliability (ICC > 0.70) was found for all CJS variables across the load-spectrum. RJS variables also had high ICC except for time parameters for early force production. All variables were significantly ($p < 0.01$) related between LPT and force platform methods with no indication of systematic bias. The LPT appears to be a valid method of assessing force under these experimental conditions.

Key Words: dynamometer, linear position transducer, validity

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[1]Musculoskeletal Biomechanics Research Lab, 1540 East Alcazar St., CHP-155, University of Southern California, Los Angeles, CA 90089; [2]Human Performance Labs, 171 Roane Fieldhouse, University of Memphis, Memphis, TN 38152.

The measurement of variables related to force expression during resistance exercise provides an indication of acute and chronic adaptations to training. Production of muscle force is a function of neural activation, muscle cross-sectional area, and contractile protein interactions (Häkkinen, Komi, & Alén, 1985; Siegel, Filders, Staron, & Hagerman, 2002). The application of force results in changes in velocity, and consequently in motion of the limbs.

Force and force related parameters have been measured using isometric (Häkkinen et al., 1985; Viitasalo, Saukkonen, & Komi, 1980), isokinetic (Weiss, Relyea, Ashley, & Propst, 1996), and dynamic constant external resistance modalities (Bosco, Belli, & Astrua, 1995; McBride, Triplett-McBride, Davie, & Newton, 1999; Rahmani, Dalleau, Viale, Hautier, & Lacour, 2000; Siegel et al., 2002). The latter systems have attempted to calculate force data by measuring displacement using a linear position transducer (LPT) or similar type of device (Harman, 1995). The LPT provides an output voltage proportional to the position of a tether. Inverse dynamic equations are applied to determine kinetics from the kinematics. A limitation to these modalities is that measurement is typically performed using machine exercises, which affects the body's ability to move freely as occurs in most sports (Stone, Plisk, & Collins, 2002).

Traditionally the inverse dynamics approach is applied to motion analysis data; however, this modality is time-consuming and not typically available in coaching or clinical settings. The use of voltage output devices is a simpler method, but the validity of this method has not been established. A concern with this modality arises from the point of attachment of the LPT tether to the barbell. This may limit the measurements to the kinematics of the barbell only, and not the lifter-barbell system. Some researchers have included mass of the lifter to the barbell in order to calculate system force, rate of force development (RFD), and power (Baker, Nance, & Moore, 2001); however, this technique has not been validated.

This study was conducted to determine the validity of the LPT in measuring free-weight resistance exercise force by comparing these measurements with vertical ground reaction forces (VGRF) measured directly with a force platform.

Methods

Two men and four women (mean ± *SD* age 24.83 yrs ± 3.31; mass 76.24 kg ± 25.90; height 170.42 cm ± 4.01) with moderate to extensive resistance exercise training background participated subsequent to written informed consent as approved by the institutional review board of the University of Memphis. Participants were required to have at least 6 months current resistance exercise experience, including performance of the parallel back squat.

They undertook two practice sessions of concentric-only (CJS) and rebound (RJS) jump squats. Jump squats were performed by squatting with a loaded barbell until the back of the thigh touched an elastic cord set so that vertical bar displacement was 10% of the participant's height. This has been observed anecdotally as the optimal displacement during the dip phase of the jerk in weightlifting, a movement similar to jump squats and known to result in high power output (Garhammer, 1993). For CJS, participants paused in the bottom position for an audible four-count before proceeding to the concentric action. For RJS, they performed the concentric action immediately after touching the elastic cord.

During the second practice session, each participant's one-repetition maximum (1-RM) in the parallel back squat was determined. Single repetitions were performed with successively increasing loads. A lift was successful if the participant could descend until the inguinal fold was lower than the patella and then rise without help, as per International Powerlifting Federation rules (2002). For all squats, supportive equipment such as a weight training belt were not allowed. Mean 1-RM relative to body mass was 1.41 ± 0.57 $\text{kg}\cdot\text{kg}_{\text{body mass}}{}^{-1}$.

Reliability was assessed with a test-retest design. Four testing sessions were conducted over a 2-week period, CJS for two sessions and RJS for the remaining two sessions. The order of test sessions was randomized. Each session involved a brief warm-up with successively increasing loads. A 5-min rest period was provided prior to the test jumps. CJS or RJS were performed with 30%, 50%, and 70% 1-RM with 1-min interset rest intervals. A 10-min rest was taken and the jumps were repeated.

Jump squats were performed on a single-component force platform capable of measuring VGRF (Major, Sands, McNeal, Paine, & Kipp, 1998). An LPT (P510-80-NJC-004-TS; Unimeasure, Corvalis, OR) was placed to the right of the force platform and the tether was attached medially to the revolving collar of a weightlifting barbell. With the participant standing, the LPT tether was vertically aligned, perpendicular to the floor (Figure 1). The LPT had a resolution of 4.920 $\text{mV}\cdot\text{mm}^{-1}$ and a repeatability of 0.015% of the full-scale voltage output. The retraction tension of the tether was 1.4 N, a negligible amount relative to the loads

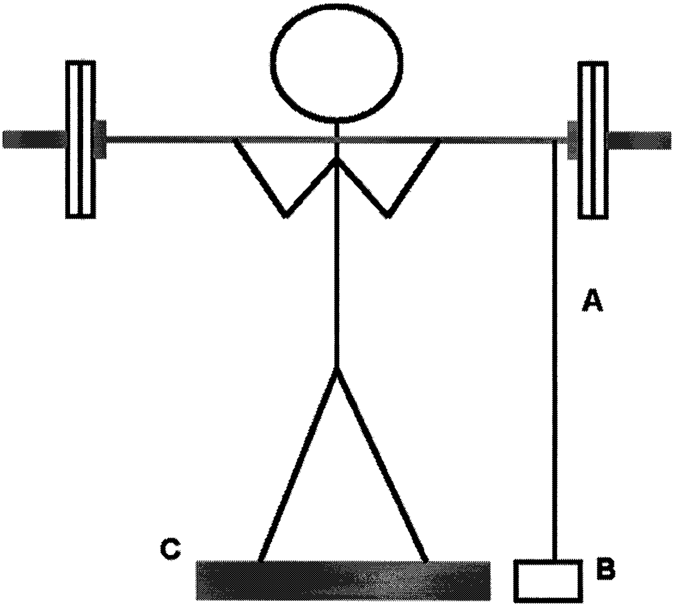

Figure 1 — Arrangement of tether (A), linear position transducer (B), force platform (C), and lifter.

and forces in this study. A 0–20 vdc signal from the force platform and a 0–5 vdc signal from the LPT were channeled via coaxial cables through a 12-bit analog-to-digital conversion system (Ariel Dynamics, San Diego) interfaced with a Pentium II computer. Data were sampled simultaneously using the Ariel Performance Analysis System (Ariel Dynamics) at a sampling frequency of 500 Hz.

Data were analyzed using BioProc2 software (D.G.E. Robertson, author/provider, Ottawa, ON). Both data signals were low-passed filtered using a 4th-order recursive Butterworth with a 50-Hz cutoff frequency. The cutoff frequency was selected following Fourier analysis of the power spectrum. Velocity and acceleration were calculated using the finite-difference technique (Winter, 1990). Gravitational acceleration was added to the calculated acceleration, which was subsequently multiplied by the mass of the participant and barbell to obtain force. At this point the calculated force-time data were digitally filtered again with a 50-Hz cutoff frequency to reduce noise, which may have been magnified following differentiation (Winter, 1990). Analysis of pilot data, including Fourier analysis of the power spectrum, revealed that the repetitive application of the filter was more effective at reducing noise without losing the signal than was a single application with a lower cutoff frequency.

Force platform and LPT instantaneous peak force and time to 20, 40, 60, 80, and 100% peak force were determined from the isometric and concentric portion of the exercise. The initiation of these phases was operationally defined as the point of lowest force. Force platform and LPT peak RFD were calculated using the finite-differences technique as described by Viitasalo et al. (1980) and the time of peak RFD was determined. Average RFD for the force platform and LPT were calculated as described by Chiu, Fry, Schilling, Weiss, and Kreider (2002):

$$\text{Average RFD} = [F(\text{peak}) - F(\text{initial})] / [t_{F(\text{peak})} - t_{F(\text{initial})}] \qquad (1)$$

Two-way random, average-measure intraclass correlation (ICC) coefficients were calculated to determine the reliability of the individual measures and to compare force data with the LPT and force platform. The minimum acceptable ICC was set a priori at ICC = 0.70 (Baumgartner & Chung, 2001). All statistical calculations were performed using SPSS 11.0 (Chicago). Differences between magnitudes were assessed using the percent standard error of measurement (*SEM*).

Results

Reliability coefficients for CJS (Table 1) were high for all variables and did not appear to be dependant on the relative load. A number of variables for RJS (Table 1) also showed high reliability. Some time factors for early force production had poor reliability during RJS. As load increased, reliability was lower for the time to various percentages of peak force. Reliability coefficients did not differ between force platform and LPT modes.

High ICC were found for all measures comparing LPT calculations to force platform measurements for both CJS and RJS (Table 2). Force values and time of occurrence were similar between both methods of measurement. These results indicate that LPT calculation of force parameters was representative of force platform measurements and that systematic bias was not present. Data from a representative trial are shown in Figure 2. The mean ± *SD* for peak force were:

Table 1 Reliability Coefficients for Concentric-Only and Rebound Jump Squats

	Concentric-Only Jump Squats						Rebound Jump Squats					
	30%		50%		70%		30%		0%		70%	
Variable	FP	LPT	FP	LPT	FP	LPT	FP	LPT	FP	LPT	FP	LPT
Peak force	1.00	0.99	1.00	1.00	1.00	0.99	0.99	1.00	1.00	1.00	1.00	1.00
Time to 20% PF	0.81	0.82	0.93	0.92	0.89	0.92	0.76	0.79	0.60*	0.64*	0.47*	0.60*
Time to 40% PF	0.86	0.80	0.94	0.93	0.87	0.90	0.00*	–0.11*	0.03*	–0.08*	0.35*	0.45*
Time to 60% PF	0.80	0.84	0.95	0.94	0.87	0.90	0.67*	0.58*	0.66*	0.70	–0.14*	–0.17*
Time to 80% PF	0.86	0.87	0.93	0.95	0.87	0.90	0.84	0.79	0.80	0.82	0.64*	0.70
Time to 100% PF	0.85	0.88	0.91	0.90	0.94	0.95	0.92	0.94	0.87	0.89	0.86	0.93
Peak RFD	0.89	0.85	0.93	0.93	0.88	0.80	0.95	0.91	0.92	0.89	0.91	0.94
Average RFD	0.90	0.70	0.95	0.93	0.94	0.92	0.96	0.97	0.98	0.92	0.96	0.92
Time of PRFD	0.91	0.81	0.97	0.95	0.92	0.93	0.19*	0.62*	0.16*	–0.03*	0.58*	0.72

* Denotes standard for reliability not met. Negative coefficient refers to very poor reliability.

Table 2 Intraclass Correlations Comparing Force Platform and Linear Position Transducer

	Concentric-Only Jump Squats			Rebound Jump Squats		
Variable	30%	50%	70%	30%	50%	70%
Peak force	0.99	1.00	0.99	0.99	1.00	0.99
Time to 20% PF	0.98	0.98	0.97	0.87	0.99	0.99
Time to 40% PF	0.99	0.99	0.99	1.00	1.00	1.00
Time to 60% PF	0.91	0.99	0.98	0.99	0.99	0.93
Time to 80% PF	0.99	0.98	0.98	0.98	0.99	0.98
Time to 100% PF	0.96	0.97	0.97	0.99	0.99	0.97
Peak RFD	0.89	0.95	0.90	0.88	0.91	0.90
Average RFD	0.94	0.98	0.96	0.93	0.96	0.94
Time of PRFD	0.93	0.99	0.99	0.75	0.98	0.98

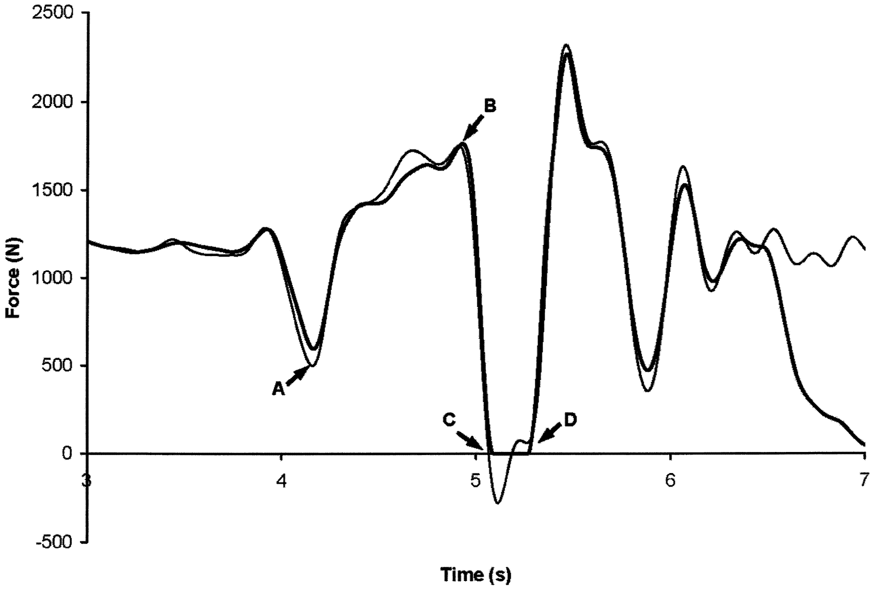

Figure 2 — Rebound jump squat force-time data for a representative trial (thick line = force platform; thin line = linear position transducer; initiation of isometric phase (A), peak [propulsion phase] force (B); take-off (C); landing (D).

CJS 30% 1-RM (FP: 2382 ± 928 N; LPT: 2585 ± 916 N; *SEM* = 3.0%); CJS 50% 1-RM (FP: 2567 ± 1091 N; LPT: 2723 ± 1174 N; *SEM* = 1.8%); CJS 70% 1-RM (FP: 2711 ± 1179 N; LPT: 2847 ± 1289 N; *SEM* = 4.5%); RJS 30% 1-RM (FP: 2350 ± 979 N; LPT: 2527 ± 1031 N; *SEM* = 4.5%); RJS 50% 1-RM (FP: 2467 ± 1158 N; LPT: 2647 ± 1251 N; *SEM* = 2.6%); and RJS 70% 1-RM (FP: 2642 ± 1224 N; LPT: 2789 ± 1382 N; *SEM* = 4.9%). The standard error of measurement of time parameters was less than 0.01 s for all conditions.

Discussion

The estimation of VGRF during jump squats with kinematic data from an LPT was found to be valid compared to that directly measured from a force platform. CJS measures were highly reliable; however, time-dependent measures for RJS were not. The tempo of the eccentric phase was not controlled, thus differences in the rate of descent may affect the storage and utilization of elastic energy. This would affect the temporal pattern of producing force, even during the concentric phase. Timing factors appear highly variable as opposed to magnitude parameters. Using an isokinetic squat modality, Weiss et al. (1996) found high reliability for force and power measures but reliability coefficients were lower for time parameters.

The high ICC and low magnitude differences for calculating force variables from displacement measurement in comparison to a force platform indicates the potential validity of the LPT as a resistance exercise measurement device. Initial use of LPT and similar devices only calculated force using barbell mass, measuring only the force applied to the barbell (Wilson et al., 1993). This may be appropriate for exercises such as the bench press in which the load displaced is primarily that of the barbell. However, for other exercises the displacement of the lifter's body accounts for a meaningful percentage of mechanical work. Baker et al. (2001) calculated system force and power by combining the mass of the participant and the barbell, but they provided no validation of this method. The current study validates this method for use with the CJS and RJS exercises.

Cavagna's (1985) single integration method determines velocity of the center of mass from force data. The current investigation established criterion validity for the estimation of VGRF via double differentiation of the displacement-time curve obtained from an LPT. Although the LPT is attached to the barbell, the displacement of the barbell during jump squats may represent the displacement of the system's center of mass and the fact that both move in a vertical and linear path. It is important to note that this validation is only applicable to the studied movement, and a bar path for a larger range of motion squat may differ from that of the COM of the system. The current study has found the inverse dynamics approach valid for the exercises and technologies used.

It is interesting to note that during the flight phase, in which VGRF should be zero, the VGRF estimated from the LPT under- and overshoots this point. This phenomenon may be explained by the oscillation of the ends of the barbell. Thus, while the point of attachment of the LPT tether to the barbell acts as a rigid body during most of the squatting motion, the elastic characteristics of the barbell introduce error during the flight phase.

Although LPT technology has been used extensively for biomechanical measurement of resistance exercise, this method has not been previously validated. The criterion validity of using an LPT to measure force variables has been established, with comparison to a force platform. Additionally, this study used the novel approach of evaluating free-weight exercise as opposed to machine exercise. Although the LPT does not replace the force platform under all circumstances, it appears to be valid in the context of the protocols performed in this study. Furthermore, due to the high relationship with force platform measures, LPT technology provides a valid representation of the movement of the center of mass when attached to the barbell during CJS and RJS.

References

Baker, D., Nance, S., & Moore, M. (2001). The load that maximizes the average mechanical power output during jump squats in power-trained athletes. *Journal of Strength and Conditioning Research*, **15**, 92-97.

Baumgartner, T.A., & Chung, H. (2001). Confidence limits for intraclass reliability coefficients. *Measurement in Physical Education and Exercise Science*, **5**, 179-188.

Bosco, C., Belli, A., Astrua, M., Tihanyi, J., Pozzo, R., Kellis, S., Tsarpela, O., Forti, C., Manno, R., & Tranqulli, C. (1995). A dynamometer for evaluation of dynamic muscular work. *European Journal of Applied Physiology*, **70**, 379-386.

Cavagna, G.A. (1985). Force platforms as ergometers. *Journal of Applied Physiology*, **39**, 174-179.

Chiu, L.Z.F., Fry, A.C., Schilling, B.K., Weiss, L.W., & Kreider, R.B. (2002). The relationship between EMG-time and isometric force-time curves [abstract]. In T. Allinger (Ed.), *Proceedings of the 6th IOC World Congress on Sport Sciences* (p. 22). Baltimore: Lippincott Williams & Wilkins.

Garhammer, J. (1993). A review of power output studies of Olympic and powerlifting: Methodology, performance prediction, and evaluation tests. *Journal of Strength and Conditioning Research*, **7**, 76-89.

Häkkinen, K., Komi, P.V., & Alén, M. (1985). Effect of explosive type strength training on isometric force- and relaxation-time, electromyographic and muscle fibre characteristics of leg extensor muscles. *Acta Physiologica Scandinavica*, **125**, 587-600.

Harman, E.A. (1995). The measurement of human mechanical power. In P.J. Maud & C. Foster (Eds.), *Physiological assessment of human fitness* (pp. 87-113). Champaign, IL: Human Kinetics.

International Powerlifting Federation. (2002). *Technical rules book of the International Powerlifting Federation*. Retrieved June 27, 2002, from http://www.powerlifting-ipf.com/IPF_rulebook-pdf

Major, J.A., Sands, W.A., NcNeal, J.R., Paine, D.D., & Kipp, R. (1998). Design, construction, and validation of a portable one-dimensional force platform. *Journal of Strength and Conditioning Research*, **12**, 37-41.

McBride, J.M., Triplett-McBride, T., Davie, A., & Newton, R.U. (1999). A comparison of strength and power characteristics between power lifters, Olympic lifters, and sprinters. *Journal of Strength and Conditioning Research*, **13**, 58-66.

Rahmani, A., Dalleau, G., Viale, F., Hautier, C.A., & Lacour, J-R. (2000). Validity and reliability of a kinematic device for measuring the force developed during squatting. *Journal of Applied Biomechanics*, **16**, 26-35.

Siegel, J.A., Filders, R.M., Staron, R.S., & Hagerman, F.C. (2002). Human muscle power output during upper- and lower-body exercises. *Journal of Strength and Conditioning Research*, **16**, 173-178.

Stone, M.H., Plisk, S.P., & Collins, D. (2002). Training principles: Evaluation of modes and methods of resistance training – A coaching perspective. *Sports Biomechanics*, **1**, 79-103.

Viitasalo, J.T., Saukkonen, S., & Komi, P.V. (1980). Reproducibility of measurements of selected neuromuscular performance variables in man. *Electromyography and Clinical Neurophysiology*, **20**, 487-501.

Weiss, L.W., Relyea, G.E., Ashley, C.D., & Propst, R.C. (1996). Reliability of selected measures of musculoskeletal function obtained during closed kinetic chain exercises at multiple velocities. *Journal of Strength and Conditioning Research*, **10**, 45-50.

Wilson, G.J., Newton, R.U., Murphy, A.J., & Humphries, B.J. (1993). The optimal training load for the development of dynamic athletic performance. *Medicine and Science in Sports and Exercise*, **25**, 1279-1286.

Winter, D.A. (1990). *Biomechanics and motor control of human movement*. New York: Wiley.

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