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Abderrehmane Rahmani · Fabrice Viale
Georges Dalleau · Jean-René Lacour

Force/velocity and power/velocity relationships in squat exercise

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Abstract The purpose of this study was to describe the force/velocity and power/velocity relationships obtained during squat exercise. The maximal force (F_0) was extrapolated from the force/velocity relationship and compared to the isometric force directly measured with the aid of a force platform placed under the subject's feet. Fifteen international downhill skiers [mean (SD) age 22.4 (2.6) years, height 178 (6.34) cm and body mass 81.3 (7.70) kg] performed maximal dynamic and isometric squat exercises on a guided barbell. The dynamic squats were performed with masses ranging from 60 to 180 kg, which were placed on the shoulders. The force produced during the squat exercise was linearly related to the velocity in each subject ($r^2 = 0.83$–0.98, $P < 0.05$–0.0001). The extrapolated F_0 was 23% higher than the measured isometric force ($P < 0.001$), and the two measurements were not correlated. This may be attributed to the position of the subject, since the isometric force was obtained at a constant angle (90° of knee flexion), whereas the dynamic forces were measured through a range of movements (from 90° to 180°). The power/velocity relationship was parabolic in shape for each subject ($r^2 = 0.94$–0.99, $P < 0.01$–0.0001). However, the curve obtained exhibited only an ascending part. The highest power was produced against the lightest load (i.e., 60 kg). The maximal power ($\dot{W}_{max}$) and optimal velocity were never reached. The failure to observe the descending part of the power/velocity curve may be attributed to the upper limitation of the velocities studied. Nevertheless, the extrapolation of $\dot{W}_{max}$ from the power/velocity equation showed that it would be reached for a load close to body mass, or even under unloaded conditions.

Key words Dynamic · Isometric · Force/velocity relationship · Extrapolated isometric force · Power/velocity relationship

A. Rahmani (✉) · J.-R. Lacour
Laboratoire de Physiologie de l'Exercice – GIP Exercice,
Faculté de Médecine, Lyon Sud, BP 12,
69921 Oullins Cedex, France
e-mail: abdel.rahmani@univ-lyon1.fr
Tel.: +33-478863135; Fax: +33-478863135

F. Viale · G. Dalleau
Centre Universitaire de Recherche en
Activités Physiques et Sportives,
Faculté des Sciences et Technologies,
Université de la Réunion,
117 rue du Général Ailleret,
97430 Le Tampon, France

Introduction

Squatting with a mass on the shoulders is one of the most widely used training exercises for the development of strength in the lower leg extensor muscles (McLaughlin et al. 1977), or for general fitness and rehabilitation exercises (Beynnon and Johnson 1996). In general, the load is set at a percentage of the maximum weight the individual can lift once with proper form and technique (the one-repetition maximum). However, the weight used is not the only parameter that must be considered in strength training. Programs using different speeds of movement have shown a velocity-specific increase in strength (Behm and Sale 1993). Training with heavy loads is used to enhance strength, whereas training with light loads improves power production (Caiozzo et al. 1981; Kanehisa and Miyashita 1983; Kaneko et al. 1983). This means that to achieve a specific performance enhancement, athletes must perform training exercises at the specific load and velocity that best correspond to the muscular performance in the competitive movement (Wilson et al. 1993). Therefore, force/velocity and power/velocity relationships are the ideal parameters to study for determining the conditions of muscular work required.

The use of force/velocity and power/velocity relationships during isokinetic (Perrine and Edgerton 1978) and ballistic (Rahmani et al. 1999) mono-articular movements, and during pluri-articular cycling movements (Hautier et al. 1996; Vandewalle et al. 1987) is now well-established. Setting the force and power/velocity relationships enables the determination of different indicators of muscle function. Some authors have assessed the theoretical maximal isometric force (F_0) and the theoretical maximal velocity (v_0), which are defined as the intersection of the force/velocity relationship with the force and the velocity axis, respectively, directly from dynamic performance (Driss et al. 1998; Vandewalle et al. 1987). Although the relationship between the dynamic and the isometric performance remains to be resolved (for review, see Wilson and Murphy 1996), no study has been conducted to validate this fact from a force/velocity relationship obtained during squat exercise. It may be useful to be able to predict isometric force directly from the extrapolation of the force/velocity relationship without the use of a force-plate. In addition, the parabolic power/velocity relationship gives a specific parameter, the maximal power ($\dot{W}_{max}$) obtained at the corresponding optimal velocity (v_{opt}; Hautier et al. 1996). These models were obtained from cycling or mono-articular exercises, which are very different from the loading and limb pluri-articular extension conditions observed in a squat movement. Whether these parameters can be assessed with a squatting exercise has yet to be established.

The purpose of this study was thus to describe the force/ and power/velocity relationships of a squatting movement by determining the different muscular parameters (i.e., F_0, $\dot{W}_{max}$ and v_{opt}), and by comparing the measured F_0 to the extrapolated theoretical F_0.

Methods

Subjects

Fifteen international alpine skiing racers volunteered and gave their informed consent to take part in the study. All of the subjects were accustomed to developing maximum effort during both isometric and dynamic squat exercises. Their mean (SD) age, height and body mass were 22.4 (2.6) years, 178 (6.3) cm and 81.3 (7.7) kg, respectively. The testing session was part of a standard evaluation procedure that was developed by the French Skiing Federation.

Tests

Isometric and dynamic tests were conducted on a modified guided horizontal barbell (Multipower Basic, Panatta Sport, Apiro, Italy) that was positioned over a Kistler force plate (Kistler type 9281 B, Kistler Instruments, Winterthur, Switzerland). For the isometric contraction mode, the tests were performed at a knee angle of 90°. For the dynamic tests, the subjects performed squat jump exercises from a 90° knee angle to full extension. Quantification of the 90° angle was performed with a goniometer (model SEEB 502, accuracy 1°, Sfernice, Nice, France). Once the position was determined, mechanical stops that were fixed into the guided barbell were positioned so that the appropriate angle was achieved.

For the isometric tests, the mechanical stops were located above and below the bar to securely fix it in the appropriate position. Subjects were instructed to perform the contraction as rapidly and forcefully as possible and to maintain it for 5 s. When the aim of testing is to record F_0, these instructions produce optimal results (Bemben et al. 1990). Subjects performed three trials and had 5 min rest between trials.

For the dynamic tests, only the concentric part of the squat was considered. The mechanical stops were positioned below the bar at the appropriate angle. Upon an auditory command, the subjects applied force as explosively as possible with an extra load of 60–180 kg (increased in 20-kg increments) on the shoulders. Subjects had to provide the fastest acceleration they could. Therefore, for the lightest loads, the subjects took off from the ground. The barbell was maintained in contact with the shoulders of the subjects throughout the motion. Subjects performed two trials at each load. Each trial was followed by a rest period of at least 3 min.

Data collection

When performing the various isometric and concentric tests, the subjects stood directly over a Kistler (9281B) force plate. The force plate was mounted according to the manufacturer's specifications. Charge amplifiers (Kistler type 9861 A, Kistler Instruments) amplified analog signals from the force-plate. The amplifiers were reset to zero before the subject stood on the plate. The force signal was linear ($<0.05\%$) over a range force of 0–10 kN. The resonant frequency of the force plate was >200 Hz.

Data were sampled at a rate of 1000 Hz for the isometric contractions and 200 Hz for the concentric ones. The sampled frequency during the isometric contractions was overestimated, but this did not influence the evaluation of F_0. This frequency was chosen to determine the isometric rate of force development included in the evaluation protocol requested by the Alpine Skiing Federation. Data were stored on a PC computer (486 DX2, 66 MHz) via electronic interface cards equipped with a 12-bit A/D converter card (National Instrument France, type PC-LPM16, Le Blanc-Mesnil, France). The signals were filtered digitally with a 12-Hz low-pass Butterworth filter with zero phase lag.

Several variables from the vertical force components were calculated from ground reaction force data over the entire sampling period for both the isometric and dynamic curves. The maximal force was identified as the highest values attained during the movement. The instantaneous vertical velocity produced during the dynamic squat was integrated from the acceleration, provided from the force signal, divided by the whole mass, after subtraction of the gravitational acceleration. The integration constant was zero because there was no initial movement. The instantaneous power was the product of the force and velocity at any given point.

Data analyses

The isometric peak force per body weight (IPF) and the dynamic peak force (DPF), which were determined from the force/time curves, were analyzed. The mean force, the mean velocity and the mean power of the push-off phase were all the average of instantaneous force, velocity and power values, respectively, measured during the period of a complete repetition. The mean of the three trials for the isometric tests and the mean of the two trials for the dynamic trials were considered as the most representative measures of muscle function and were used in further analyses. Bearing in mind that few data points were available, the linear force/velocity model proposed by other authors (e.g., Bosco et al. 1995; Vandewalle et al. 1987) fit the measured data best. The use of a non-linear force/velocity model would not consistently increase the r^2 values. Therefore, it was logical to use a second-degree polynomial model to describe the power/velocity curve, since this relationship is derived from the product of the force and the velocity. These curves were extrapolated to obtain F_0 and v_0 (which correspond to the intercept of the force/velocity curve with the force and the velocity axis, respectively), v_{opt} and $\dot{W}_{max}$ (corresponding to the velocity and power at the highest point of the power/velocity curve).

Statistical analysis

Data are presented as the mean (SD). The level of statistical significance was set at $P < 0.05$ for all statistical procedures. In agreement with the statistical norms (Vincent 1995), the trial-to-trial reliability was tested by assessing the intraclass correlation coefficient (IC) between the three trials performed during the isometric contractions, and between the two trials performed during the dynamic contractions. The IC was calculated from a one-factor repeated-measures analysis of variance. The standard error of the mean (SEM%) was also computed to test the reliability.

Pearson product moment correlation coefficients (r) were used to determine the significance of the force/velocity and power/velocity relationships. A paired t-test was used to determine whether there were significant differences between the isometric and dynamic parameters. The coefficient of variation (CV%) was determined to compare the variability of the dynamic and isometric measurements, and to determine the variability of the slope of the force/velocity relationship.

Results

Reliability

The mean values of the peak forces, the trial-to-trial IC and the SEM% for both the isometric and dynamic variables are presented in Table 1. The IC for the isometric contraction was 0.98, and varied from 0.69 to 0.88 for the dynamic contractions. The SEM% was less than 3% for both the isometric and dynamic contractions.

Force/velocity relationship

The courses of the average forces developed during squat exercises performed with various loads (from 60 to 180 kg) by the whole group ($n = 15$) and, as an example, by a typical subject, as a function of the average velocity of the barbell are shown in Fig. 1. The force/velocity relationship exhibited a significantly linear shape in the whole group ($r^2 = 0.99$, $P < 0.001$; $F = -13.4\ v + 41.2$) and for each subject ($r^2 = 0.83$–0.98, $P < 0.05$–0.0001). The force generated during the dynamic squat increased with the resistance lifted. The mean CV% of the slope was 25.8% (extreme absolute values: 591–1495). The mean (SD) F_0 and v_0 extrapolated from the force/velocity relationship were 40.9 (3.3) $\mathrm{N \cdot kg^{-1}}$ and 3.31 (0.75) $\mathrm{m \cdot s^{-1}}$, respectively. The mean (SD) IPF measured from the isometric squat exercise was 31.7 (7.8) $\mathrm{N{\cdot}kg^{-1}}$. The F_0 was 23% higher than IPF ($P < 0.001$), and the two were not correlated. The peak force was reached at a mean (SD) knee angle of 109.7 (2.7)°, whatever the load ($P < 0.05$). The CV% was 24.6% for IPF and 6.9 (0.6)% for the DPF.

Table 1 Peak forces [$\dot{W}_{peak}$, presented as the mean (SD)], intraclass coefficient of reliability (*IC*), standard error of mean (*SEM%*) and coefficient of variation (*CV%*) of the isometric and dynamic variables

Load (kg)	$\dot{W}_{peak}$ ($\mathrm{N{\cdot}kg^{-1}}$)	IC	SEM%	CV%
Isometric	31.7 (7.8)	0.98	2.6	24.6
60	32.9 (2.5)	0.88	2.0	7.5
80	34.6 (2.2)	0.69	2.9	6.4
100	36.3 (2.4)	0.88	2.1	6.7
120	37.9 (2.5)	0.84	2.2	6.7
140	34.5 (2.6)	0.84	2.0	7.5
160	41.3 (2.6)	0.88	1.8	6.2
180	43.3 (3.3)	0.87	1.7	7.7

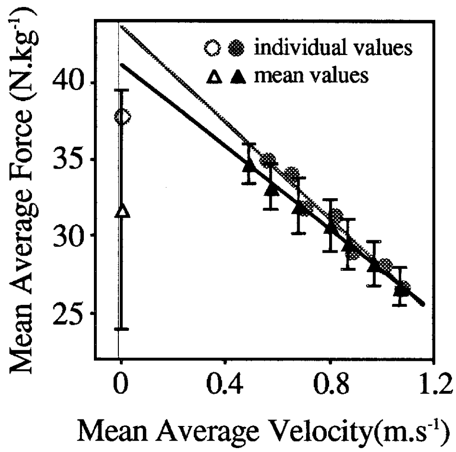

Fig. 1 Courses of mean forces (in $\mathrm{N{\cdot}kg^{-1}}$) developed during squat exercises performed with various loads (from 60 to 180 kg) by the whole group (*triangles*, $n = 15$) and, as an example, by a typical subject (*circles*), as a function of the average velocity of the barbell (in $\mathrm{m{\cdot}s^{-1}}$). The *open symbols* represent the measured isometric force. Values of the whole group are presented as their mean and standard deviation

Power/velocity relationship

The courses of the average powers developed during squat exercises performed with various loads (from 60 to 180 kg) by the whole group ($n = 15$) and, as an example, by a typical subject, as a function of the average velocity of

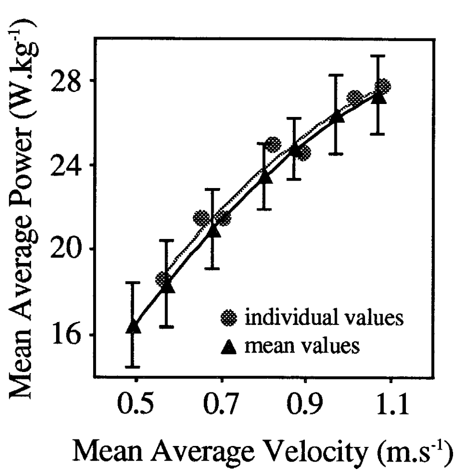

Fig. 2 Courses of the average powers (in $\mathrm{W{\cdot}kg^{-1}}$) developed during squat exercises performed with various loads (from 60 to 180 kg) by the whole group (*triangles*, $n = 15$) and, as an example, by a typical subject (*circles*), as a function of the average velocity of the barbell (in $\mathrm{m{\cdot}s^{-1}}$). Values of the whole group are presented as their mean and standard deviation

the barbell are drawn in Fig. 2. The power/velocity relationship was described by a second-order function for each subject ($r^2 = 0.94–0.99$, $P < 0.01–0.0001$). The power decreased as the load increased. The curve obtained exhibited only an ascending part. $\dot{W}_{max}$ and v_{opt} were never reached. The mean (SD) extrapolated $\dot{W}_{max}$ and v_{opt} were 30.4 (4.5) W·kg^{-1} and 1.51 (0.41) m·s^{-1}, respectively.

Discussion

Reliability

According to the statistical norms (Vincent 1995), the reliability coefficients reported in this study were very good for IPF (0.98) and moderate to good for the dynamic contractions (IC = 0.69–0.88 for DPF). These coefficients are in line with those described previously for isometric and dynamic contractions. The reliability coefficients have been shown to vary from 0.85 to 0.99 during isometric contractions (Bemben et al. 1992; Wilson et al. 1993), from 0.92 to 0.98 in weightlifting contractions (Hennessy and Watson 1994; Hortobagyi et al. 1989), or higher than 0.9 during isokinetic contractions (Taylor et al. 1991). The low SEM% value (< 3%) supported the good reliability of the squat exercise as compared with the method error encountered during isokinetic leg-press contractions (from 2.0 to 9.8%, Vandervoort et al. 1984) or isokinetic leg extensions (> 5%; Sale 1979). The good reproducibility of both the isometric and dynamic squats shows that the squat exercise is a reliable exercise that can be used to quantify the improvement following strength training from one session to another or during rehabilitation interventions.

Force/velocity relationship

The squat exercise exhibited a linear relationship between force and velocity in the whole group ($P < 0.05$). This linear relationship is in agreement with those obtained during cycling exercise, which is another pluri-articular movement (Vandewalle et al. 1987). From a practical point of view, this linear relationship, obtained from squat exercises, makes it possible to evaluate the strength values produced at different loads, and the comparison of the results from one session to another at a given load. The slope of the force/velocity relationship exhibits major variability (CV% = 25.8%) in this homogeneous group. Whether or not this slope is related to muscle fiber composition remains to be elucidated. In addition, the force/velocity relationship can be used to evaluate the resistance-training effect on the movement either by an effect on the maximal strength developed or by an effect on the v_0 achieved. The effect of training on the shape of force/velocity curves is related to the training loads and velocities used. This type of strength training results in improvements in all portions of the force/velocity curve: changes in the high force portion of the curve are essentially due to strength training, while changes in the small force portion are mainly due to power training (for review see Morrissey et al. 1995).

Some authors have assessed the F_0 of cycling exercise by extrapolating the force/velocity curve up to the force produced at null velocity (i.e., the intersection of the curve with the force axis; Butelli et al. 1996; Vandewalle et al. 1987). Compared to these studies, the F_0 developed during squatting exercise is higher [41.0 (3.3) N·kg^{-1} in this study vs 2.7 (0.2) N·kg^{-1} in volleyball players (Butelli et al. 1996) or 2.7 (0.3) N·kg^{-1} in sprinters (Vandewalle et al. 1987)]. This may be attributable to the fact that in cycling exercise the force is produced by the two legs alternatively, whereas in squat exercise the trunk muscles participate in the movement in addition to the leg muscles. Moreover, the area of the force application is smaller in cycling, and consequently less effective than the area used during squat performance. This extrapolation would avoid the need for isometric contraction. However, in the present study, the extrapolated F_0 was 23% higher than the obtained IPF. Part of the overestimation can be attributed to the position of the subject, which influences the isometric force production (Sale 1991). Indeed, the isometric force was obtained at an arbitrarily fixed angle (i.e., 90 ° of knee flexion), whereas the dynamic force was measured through a range of movements (from 90 to 180 °). The force produced against the different loads increased to reach a maximum for an approximately 110 ° knee angle before decreasing. In the same way, Häkkinen et al. (1987) showed that the forces produced during mono-articular knee extensions increased until reaching a maximal force for a knee angle of approximately 120 °, whatever the lifted load, for all the subjects. Furthermore, Murphy et al. (1995) stated that the best angle at which to perform isometric tests might be the joint angle at which F_0 is developed in the performance of interest, approximately 110 ° in this study. Taking into account this and the more favorable lever arm, the measurement of isometric force at 110 ° is likely to give a result closer to F_0.

The difference between the two measurements may also result from the instructions given to the subjects. During dynamic contractions, the force had to be produced as explosively as possible. The dynamic contractions lasted less than 1 s, whereas during the isometric contraction the subjects had to contract as forcefully as possible and to maintain this contraction for 5 s. One can imagine that performing an explosive contraction against an immovable load could produce a higher force. This phenomenon is readily visible on force/time curves obtained under different instructions (Bemben et al. 1990).

Finally, the group was more homogeneous for dynamic than for isometric performances (Table 1). Nevertheless, alpine skiing is essentially characterized by an isometric or low contraction velocity (Tesch 1995). Despite their ability to produce a high level of force during their training activities, the large CV% value (24.6%)

obtained during isometric maximal force compared to those of mean dynamic forces is likely to reflect the subjects' discomfort and the neural difficulty of producing an isometric contraction (Pryor et al. 1994). Moreover, clear differences in activation patterns between isometric and dynamic contractions at the same angle have been demonstrated (Murphy and Wilson 1996), suggesting that motor units are recruited preferentially at certain positions or angles (Caldwell et al. 1993). A larger knee angle during the isometric measurement might produce a lower variability of the measurement, as is the case during the dynamic contractions.

Power/velocity relationship

The power/velocity relationship is fitted well by a square mathematical function (Bosco et al. 1995). From this relationship, $\dot{W}_{max}$ can be determined as another muscular characteristic. A precise evaluation of $\dot{W}_{max}$ and the corresponding v_{opt} has its importance since these parameters have been related to the muscle fiber type (Hautier et al. 1996). In this study, the power/velocity was well defined by a parabolic curve ($P < 0.01$; Fig. 2), but in the range of loads used, the maximal power reached for the lightest load lifted did not correspond to $\dot{W}_{max}$. Taylor et al. (1991) obtained similar results with power and endurance athletes performing isokinetic leg extensions. The failure to observe the descending part of the polynomial power/velocity curve can be attributed to the upper limitation of the velocities studied. Skiers have a high level of isometric force but a low level of power. We did not expect that $\dot{W}_{max}$ would be reached against the body mass. This choice caused no limitation in determining the force/velocity relationship, but did for the power/velocity relationship. Moreover, in isolated muscles, $\dot{W}_{max}$ was obtained when the strength was close to 35–40% of F_0 and the shortening velocity was close to 35–40% of v_0 (Hill 1938). In this study, $\dot{W}_{max}$ is supposed to correspond to a lower percentage of F_0. If one extrapolates the power/velocity relationships of the studied skiers, one can show that $\dot{W}_{max}$ would be reached for a load close to the body mass, or even 5–15 kg lower. Further studies are needed to extend the force/velocity relationship by measuring the force produced under artificially unloaded conditions.

Conclusion

The results of this study demonstrate clearly that due to the high reproducibility of the measurement, squat exercise is a reliable method for strength evaluation. Analyses of muscle performance at different speeds of muscular contraction are possible using different loads. The force/velocity and power/velocity relationships exhibit the same shape as those described previously with other ergometers for mono- or pluri-articular movements. Nevertheless, the extrapolation of F_0 from the force/velocity relationship may induce serious pitfalls. A direct measurement of isometric force is more effective. In a comparable manner, the determination of $\dot{W}_{max}$ and v_{opt} would require performing squat exercise with the lightest loads. However, the range of velocity transfer induced by the load used can be explored and thus, load assignment can be more objectively defined. The squat force/velocity relationship provides a useful tool for coaches and scientists to better explore velocity specificity induced by load assignment in order to monitor the effect of strength programs on the dynamic performance from low to high muscular contraction velocities.

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