Influence of Squatting Depth on Jumping Performance

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[1]*Department of Human Movement Science & Athletic Training, Institute of Sports Sciences, Goethe-University Frankfurt am Main, Germany;* [2]*Department of Physiology, Australian Institute of Sport, Canberra, Australia;* [3]*School of Human Movement Studies, Charles Sturt University, Bathurst, Australia*

Abstract

Hartmann, H, Wirth, K, Klusemann, M, Dalic, J, Matuschek, C, and Schmidtbleicher, D. Influence of squatting depth on jumping performance. *J Strength Cond Res* 26(12): 3243–3261, 2012—It is unclear if increases in 1 repetition maximum (1RM) in quarter squats result in higher gains compared with full depth squats in isometric force production and vertical jump performance. The aim of the research projects was to compare the effects of different squat variants on the development of 1RM and their transfer effects to Countermovement jump (CMJ) and squat jump (SJ) height, maximal voluntary contraction (MVC), and maximal rate of force development (MRFD). Twenty-three women and 36 men (mean age: 24.11 ± 2.88 years) were parallelized into 3 groups based on their CMJ height: deep front squats (FSQ, $n = 20$), deep back squats (BSQ, $n = 20$), and quarter back squats (BSQ¼, $n = 19$). In addition, a control group (C, $n = 16$) existed (mean age: 24.38 ± 0.50 years). Experimental groups trained 2 d·wk^{-1} for 10 weeks with a strength-power block periodization, which produced significant ($p \leq 0.05$) gains of the specific squat 1RM. The FSQ and BSQ attained significant ($p \leq 0.05$) elevations in SJ and CMJ without any interaction effects between both groups ($p \geq 0.05$). The BSQ¼ and C did not reveal any significant changes of SJ and CMJ. The FSQ and BSQ had significantly higher SJ scores over C ($p \leq 0.05$). The BSQ did not feature any significant group difference to BSQ¼ ($p = 0.116$) in SJ, whereas FSQ showed a trend toward higher SJ heights over BSQ¼ ($p = 0.052$). The FSQ and BSQ presented significantly ($p \leq 0.05$) higher CMJ heights over BSQ¼ and C. Posttest in MVC and MRFD demonstrated no significant changes for BSQ. Significant declines in MRFD for FSQ in the right leg ($p \leq 0.05$) without any interaction effects for MVC and MRFD between both FSQ and BSQ were found. Training of BSQ¼ resulted in significantly ($p \leq 0.05$) lower MRFD and MVC values in contrast to FSQ and BSQ. Quarter squat training elicited significant ($p \leq 0.05$) transfer losses into the isometric maximal and explosive strength behavior. These findings therefore contest the concept of superior angle-specific transfer effects. Deep front and back squats guarantee performance-enhancing transfer effects of dynamic maximal strength to dynamic speed-strength capacity of hip and knee extensors compared with quarter squats.

Key Words maximal strength, exercise specificity, stretch-shortening cycle, squat jump, countermovement jump, maximal rate of force development (MRFD)

Introduction

Developing high explosive- and speed-strength levels requires variation of different program parameters (like different exercises, intensities, and training methods) during the preparation and competition period. Within a macrocycle for speed-strength events, designing of strength training mesocycles is therefore necessary (112). The primary goal of general strength training consists of the periodized use of hypertrophy and strength-power phases to improve single impulse size (84). There are still concomitant tasks of technique training required in the long run to enhance the transfer of the gained maximal strength and speed-strength capacity to the competition movement (112). For this transfer problem, some authors (106,108) suggest–as part of the general strength training–the execution of maximal strength exercises in the specific pattern of the competition movement, that is, in certain amplitudes of the involved joints. According to Wilson (108) in most speed-strength activities, peak force is developed only within 140–180° of knee extension. Hence, for explosive movements, which consist of a limited acceleration distance, impulse size depends on a steep rate of force development (RFD). Performing angle-specific strength training is based on the conception of limiting "accentuated muscle strength actions" (106, 118) to the joint

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26(12)/3243–3261

Journal of Strength and Conditioning Research
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angles of the target movement, where maximum efforts of force development are required. In this case, there should be no necessity for the execution of deep squats, because the development of the dynamic maximal strength of the relevant muscles occur beyond the targeted activity range (118). Accordingly, for track and field and team sports many authors advise sport-specific strength training with quarter squats (54,56,57,89,108,116). There are no studies which compared the effects of periodized maximal strength training in quarter back squats, deep back, and front squats on vertical jump performance and angle-specific isometric force production.

The Influence of General Strength Training in Different Squatting Depths for the Development of Vertical Jump Performance

Generally, the Olympic barbell squat can be classified into 3 fundamental variations: high bar back squat, low bar back squat (31,76,114), and the front squat (31,76). These 3 squat versions can be performed to different knee angles. The deep squat is carried out to 40–45° of knee extension (17,114). With the parallel squat, the knee angles differ in the parallel squat position between 60 and 70°, depending on the variation. The inguinal fold is in a straight horizontal line with the top of the knee musculature (31). The half squat is performed to 80–100° (17,56,109,115), and the quarter squat is executed to 110–140° of knee extension (17,54,79,108,115). The classification for deep (17,114) and parallel squats (31,114) is based on video analyses of weightlifters and powerlifters.

Many training interventions between 5 and 24 weeks with subjects of low to high performance level, which elicited significant increases of 1RM in deep or parallel back squats, proved significant enhancements of speed-strength performance in concentric muscle action (SJ) (40,42,44,80,111) and to the long stretch-shortening cycle (SSC) (5,7,8,33,40,42,47–49,53,65,92,94,95,102,111). However, short-term strength training studies over 5 weeks, carried out with basketball players (51) and football players (52) demonstrated an insufficient duration in increasing the speed-strength ability of the long SSC.

Studies with subjects of low performance level, training in half back squats over 7.5–10 weeks to gain maximal strength, produced significant increases of vertical jump height in SJ (4,19,22,23,46,98–100) and long SSC (22,98,99,109,117). However, many training interventions with soccer players (4,19,50,60,81) and handball players (36), who performed their sport-specific training in conjunction with a general strength training in half back squats between 6 and 13 weeks, did not demonstrate any performance-enhancing transfer effects to speed-strength capacity of the long SSC (4,19,36,50,60,81) and to the SJ (36,50,60,81). Both Cormie et al. (23) and Ugrinowitsch et al. (100) confirmed these results within a general strength training in increasing the 1RM of half back squats over 10 and 8 weeks, which showed no increments for the jumping performance in the long SSC.

Wilson et al. (110) determined the effects of general strength training with high loads in machine based quarter back squats (120°) over 10 weeks (2 d·wk^{-1}). The strength trained subjects ($n = 15$) achieved significant gains in SJ (6.8 ± 4.9%, $p \leq 0.05$) and CMJ (5.1 ± 7.5%, $p \leq 0.05$) heights. These vertical jump tests were performed in the same apparatus (plyometric power system), which was used for strength training.

A direct comparison between training groups, who executed either machine based parallel or quarter squats (joint angles were not reported), was published by Weiss et al. (105). Quarter squats were performed to half of the parallel squat position (~125°). Training groups included untrained subjects ($n = 6$), who followed a strength training over 9 weeks (3 d·wk^{-1}). Training of both groups did not elicit any significant changes of vertical jump performance in long SSC and short SSC (drop jumps).

The Influence of General Strength Training in Different Squatting Depths for the Development of Isometric Force Production

In the studies of Hoff and Helgerud (50) and Young and Bilby (117) over 8 and 7.5 weeks, the execution of half back squats (90°) elicited significant elevations of 1RM (33.7%, $p = 0.000$; 21.0%, $p \leq 0.01$) and produced significant increments in MVC (9.6%, $p \leq 0.05$; 12.4%, $p \leq 0.01$) and maximal RFD (MRFD; 52.3%, $p \leq 0.05$; 68.7%, $p \leq 0.01$). Isometric testing was performed in a smith machine in 90° (50) and 100° knee angle (117). The subjects of both training studies were instructed to lift the weight with maximal-explosive effort. These alterations of the isometric force-time curve indicate angle-specific adaptations of the training exercise (10,32,58,64,70,96,104). Although increases of MVC are verified by strength training in deep back squats ([39,41], knee angle: 107°; [8], knee angle: 90°), this cannot be confirmed for MRFD ([39], knee angle: 107°; [111], knee angle 120°). However, there are differences in training structure (periodized or nonperiodized), training methods, duration (7.5–24 weeks) and testing methods (knee angle, unilateral or bilateral strength action, leg extension test, smith machine, leg press). These factors complicate meaningful comparisons between different research groups.

In the study of Wilson et al. (110), quarter back squat training (120°) with maximal effort repetitions (6–10 reps., 3–6 sets, 80–90% 1RM, 2 d·wk^{-1}) produced significant increases of MVC (16.2 ± 21.5%, $p \leq 0.05$) without any changes of MRFD (knee angle 135°). Based on the findings of Hoff and Helgerud (50) and Young and Bilby (117), a strength training duration of 10 weeks should demonstrate significant increments of MRFD, if the isometric strength test is performed in the same knee angle that occurred in the turning point of the quarter squat.

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Research Questions

Due to the very challenging movement pattern, the execution of the deep squat with subjects of a low performance level underlies distinct adaptations in intermuscular coordination (83). Additionally, the knee extension strength is limited by the disadvantage of the long moment arm of the turning point. Therefore, the maximal strength of the knee and hip extensors is far away from maximal strength developing conditions (108,118). Rising extension causes reduced strength application (62) and reduced activity levels of m. vastus lateralis et medialis (43,66) and m. rectus femoris (43) in joint positions, where the quarter squat allows the accomplishment of comparatively supramaximal loads. Graves et al. (37) demonstrated higher gains in training loads within the training amplitude for these subjects, who performed eccentric-concentric leg extensions in the activity range with maximal strength developing potential (120–180° knee extension) compared with a training in full range of motion. Therefore, the higher leg extension strength past 120° should lead to higher increases of angle-specific 1RM in quarter back squats compared with strength training in deep squats (108). The study of Weiss et al. (105) was not able to confirm a higher strength increase in angle-specific 1RM following quarter squat training. Strength training to failure was not possible under this condition.

The First Research Question is

Does periodized maximal strength training in the quarter back squat lead to higher gains in angle-specific 1RM compared with periodized maximal strength training in deep front and back squats?

Training in parallel back squats over 12 weeks produced higher increases in muscle cross-sectional area (CSA) of the leg extensors than training in quarter back squats to 110° (79). Advocates of training in a full range of motion state that the greater morphological adaptations of the leg extensors from deep squats can be more advantageous on the development of speed-strength ability than quarter squats in the long term (76,119). But in *short-term strength training* with subjects of low performance level, neural adaptations dominate, which are the main determinant of increases in motor performance up to 12 weeks (39,41,83). The greater angle-specific strength development of the quarter squat is suggested to provide higher transfer effects of force application into the acceleration process of reactive and concentric speed-strength performance than deep squats (108). Despite higher weight loads, the very small movement amplitude in the extension range of quarter squats should lead to a low stimulus duration per performed repetition (57,115). Therefore providing a neural stimulus within the specific joint range of the quarter squat should have greater conformity with the neural motor pattern of vertical jumps than a stimulus applied over a full range of motion (deep squats).

Hence, the Second Research Question of these Research Projects is

Does periodized maximal strength training in quarter back squats lead to higher enhancements of vertical jump performance compared with periodized maximal strength training in deep front and back squats?

The term speed strength means the ability of the neuromuscular system to produce an impulse as large as possible within a given time (86). Impulse size is dependent on the MRFD, the dynamically realized maximal force (*peak force*) and on the duration of the force effect (*impulse duration*). Impulse duration is determined by the available acceleration distance and basic conditions of the acceleration characteristics (86). For explosive motion sequences with strictly limited acceleration distance, impulse size is dependent on a steep RFD. For greater transfer effects, some authors suggest (54,89,106,108,116,118) to enhance the maximal and explosive strength ability within the motion amplitude of the target movement. Longitudinal studies with isometric strength training produced the highest increments of electromyography (EMG) signals in the trained joint angles in comparison with the nontrained (10,104). According to Wilson (108), periodized maximal strength training in quarter squats, which produces greater tension stimuli, should elicit a reduction of neural inhibition of the hip and knee extensors (reducing the strength deficit) in the exercised joint angles than deep squat training. Reducing the strength deficit "allows a greater number of motor units to be recruited and for the activated motor units to be fired at higher rates" ([108], p. 122) to reach their full tetanus (15). Provided that the weight is moved with maximal effort in a final strength-power phase, periodized maximal strength training in quarter squats should peak in a more rapid recruitment, higher innervation frequencies (24,101) and a more synchronized discharge pattern of the α-motoneurones between agonists and synergists (72). By using the same knee angle that occurred in the turning point in quarter squat training, these angle-specific adaptations (50,117) should be mirrored in changes of the isometric force-time curve with superior enhancements both in MVC and MRFD of isometric leg press.

Hence, the Third Research Question of the Research Projects is

Does periodized maximal strength training in quarter back squats elicit greater gains in MRFD and MVC in 120° knee angle compared with periodized maximal strength training in deep front and back squats?

Methods

Experimental Approach to the Problem

To assess the 3 stated research questions, a longitudinal experimental design involving 10 weeks of periodized maximal strength training was chosen. It has to be examined, which squat version provides the highest increases of vertical jump performance and isometric force production. For this purpose, we compared the effects of periodized maximal strength training in quarter back squats (120° of knee

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Table 1. Subject characteristics at baseline.*

Group	N	Age (y)	Height (cm)	Body mass (kg)
		Mean ± SD		
FSQ	20	24.60 ± 0.46†	173.35 ± 2.51	71.02 ± 14.07
BSQ	20	25.00 ± 0.97†	173.68 ± 1.92	71.55 ± 12.34
BSQ¼	19	22.42 ± 0.35	179.14 ± 1.75	76.50 ± 8.56
C	16	24.38 ± 0.50†	175.56 ± 1.58	75.28 ± 9.33

*Group FSQ = deep front squat; group BSQ = deep back squat; group BSQ¼ = quarter back squat; group C = control.

†Significant group difference ($p \leq 0.05$); FSQ, BSQ, C > BSQ¼.

extension) and deep front and back squats (below parallel) on the development of 1RM and their specific transfer effects to CMJ and SJ height and maximal voluntary contraction (MVC) and MRFD in an isometric leg press (120° of knee extension). According to the best of the author's knowledge, this is the first comparison study that included front squats. Many training studies with half back squats demonstrated no performance-enhancing transfer effects into speed-strength capacity of the long SSC (4,19,23,36,50,60,81,100) and the SJ (36,50,60,81). Consequently, for a meaningful comparison, the use of deep squats and quarter squats was preferred because the specific adaptation processes of these 2 squatting depths are associated with different angle-specific adaptations.

The following parameters were assigned as *dependent variables*: Countermovement Jump (CMJ) height, Squat Jump (SJ) height, MVC, and MRFD in unilateral isometric leg press (120° knee extension), 1 repetition maximum (1RM) in deep front squat (FSQ), deep back squat (BSQ), and quarter back squat (BSQ¼). The training exercises of the 3 groups (FSQ, BSQ, BSQ¼) plus control were designated as the *independent variables*.

Subjects

Twenty-three female and 36 male physical education students (mean age: 24.11 ± 2.88 years, body mass: 73.46 ± 11.45 kg, body height: 175.37 ± 8.89 cm) volunteered for this study and were recruited from the Institute of Sports Sciences Frankfurt am Main (Table 1). The majority of the subjects had low strength training experience. Testing and training were performed during the summer term. Pretest values of body weight (BW) and body height did not show any statistically significant difference between the four groups. The subjects of group BSQ¼ had a significantly lower mean age than those of group C ($p \leq 0.05$), group FSQ ($p \leq 0.05$), and group BSQ ($p \leq 0.05$).

Each subject was informed of the experimental risks of the research and signed an informed consent document before the investigation. The research design was granted by an institutional review board for use of human subjects. These research projects were granted by Federal Institute of Sports Sciences, Germany. Prerequisite for participation in the study was proper execution of technique in the deep front squat and deep back squat. In comparing relative strength gains of the lower extremity over 12 and 10 weeks, men and women demonstrated no sex-related statistical differences (55,107). It is assumed, that the present subject population did not demonstrate any gender-specific differences within the 10-week strength training period as well. Therefore, it is justified to collapse the results of the tested parameters of both men and women in each group.

Procedures

According to their CMJ height, the subjects were parallelized and assigned to 1 of either 3 training groups: group FSQ (n = 20) performed deep front squats, group BSQ (n = 20) executed deep back squats (high bar), both with free weights. Group BSQ¼ (n = 19) carried out quarter back squats to 120° of knee extension in a Smith machine with an additional *horizontal movement plane*. This was necessary to minimize the risk of injury because the subjects had to deal with very high weight loads (Tables 3 and 7). To maintain the movement range in the knee joint, subjects of group BSQ¼ carried a goniometer on their right knee. Investigators supervised the movement range of all the groups during training and testing. In addition, a control group existed (n = 16), whose subjects were not allowed to perform any strength training exercises for the lower extremities during the time of this investigation. Statistical homogeneity of the CMJ height was warranted at baseline for all the groups, tested by 1-way analysis of variance (ANOVA).

The time of day testing was kept constant. The subjects were advised to eat a meal 3 hours before testing; however, nutrition and hydration status were not controlled and were beyond the scope of this study. One week before testing, the subjects of the experimental groups were familiarized with both deep front squats and deep back squats. Under supervision of the investigators, the subjects performed 3 sets with 12 repetitions of each squat variant with proper form for 2 days, separated by 2 days of rest. Three days after the last pretest, strength training groups followed a strength-power periodization program over 10 weeks for 2 d·wk^{-1} on Monday and Thursday or Tuesday and Friday (Table 2). The effect of strength-power periodization in increasing dynamic maximal strength has been confirmed in several studies (7,60,81,92,94,102,111). Blocks 1 and 2, each with 4 weeks of duration, included hypertrophy strength training with

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Table 2. Load dynamics of the 3 experimental groups during the entire 10 weeks of the periodized strength training period.

Week	Block	Sets	Repetitions	Rest of set (min)
1–4	Hypertrophy phase I	5	8–10RM	5
5–8	Hypertrophy phase II	5	6–8RM	5
9–10	Strength-power phase	5	2–4RM	5

progressive intensity to enhance morphological adaptations. Block 3 was characterized by maximal effort repetitions to improve intramuscular coordination, which is associated with the voluntary innervation of the new gained contractile structures (strength-power phase) (86). This method was used in the final 2 weeks, because it has been proven of high value in maximizing dynamic speed-strength performance of the lower extremities (46,80,111).

Relative strength values (kilograms 1RM per kilogram body mass) of pretest and posttest are shown in Table 3 for each group.

Bouncing the bar in the eccentric-concentric transition phase was not allowed in any training session. The subjects performed each set to momentary muscular failure in the last 2 repetitions of the targeted repetitions scheme (forced reps). The investigators provided spotting and strong verbal encouragement. If necessary, the resistance was adapted for 2.5–10 kg for the next set or next training session so that the subject was able to perform the particular repetition scheme. The subjects were permitted to train their usual strength training programs with the exception of exercises for the lower extremities and the lower back. Exclusion criterion was missing >2 of the training sessions.

Testing

Pretest I in determining 1RM of deep back squats and pretest II in measuring 1RM of deep front squats and quarter back squats were carried out 14 and 11 days before training. Pretest III and pretest IV both included measurements of vertical jump performance and isometric force production. Both vertical jump and isometric strength testing were performed 7 and 4 days before the first training session. Posttest I in determining 1RM of deep back squats occurred in the last training session, followed by regular training of the groups. Posttest II involved measuring 1RM of deep front squats and quarter back squats which was carried out 3 days after the last training session. Posttest III and posttest IV both included testing vertical jump performance and isometric force production which were conducted 7 and 14 days after the last work-out. Only the best trials were used for statistical comparison and are designated as "Pretest" and "Posttest."

Dynamic Maximal Strength Testing. Pretest I included the determination of 1RM of the deep back squat (high bar). The barbell was positioned on the trapezius pars descendens below the seventh cervical vertebra. The subjects stand erect with self-selected width of the feet, flexed their knees to reach the deep squat position with proper form (breaking parallel) and returned to starting position. Attempts failed when the subjects rounded their back or were not able to flex the knees to the desired and maximal possible depth. Determination of 1RM was fulfilled within a maximum of 5 trials. Rest between attempts was at least 5 minutes.

Pretest II took place 3 days after pretest I. At first, 1RM was determined in deep front squats and second in quarter back squats to 120° of knee extension.

In the front squat, the barbell was held above the art. sternoclaviculares, in which the upper arms were held in pronated posture parallel to the bottom. The subjects stood

Table 3. Relative strength values (kilogram 1-repetition maximum per kilogram body mass) of all groups in pretests and posttests (mean ± *SD*).*

	Pretest			Posttest		
Group	Deep front squat	Deep back squat	Quarter back squat	Deep front squat	Deep back squat	Quarter back squat
FSQ	1.01 ± 0.26	1.15 ± 0.27	2.96 ± 0.57	1.26 ± 0.23	1.36 ± 0.26	3.22 ± 0.47
BSQ	0.92 ± 0.28	1.12 ± 0.33	2.62 ± 0.68	1.12 ± 0.26	1.41 ± 0.30	3.18 ± 0.46
BSQ¼	0.95 ± 0.24	1.13 ± 0.32	2.87 ± 0.43	0.94 ± 0.24	1.07 ± 0.30	3.89 ± 0.33
C	0.87 ± 0.24	1.01 ± 0.29	2.48 ± 0.50	0.87 ± 0.24	1.00 ± 0.27	2.50 ± 0.48

*Group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).

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TABLE 4. Mean values, *SD*s, and percentage changes of vertical jump heights of all groups from pretest to posttest.*

		Mean ± *SD*		
Variable	Group	Pretest	Posttest	Change (%)
CMJ (cm)	FSQ	38.27 ± 8.37	41.25 ± 8.57	8.29 ± 6.15†‡§
	BSQ	37.45 ± 10.2	40.31 ± 10.9	7.79 ± 5.43†‡§
	BSQ¼	40.99 ± 7.26	40.87 ± 6.90	−0.01 ± 6.77
	C	35.49 ± 6.55	34.79 ± 4.91	−0.87 ± 9.06
SJ (cm)	FSQ	35.10 ± 8.11	37.32 ± 7.65	7.19 ± 7.33†‖
	BSQ	34.80 ± 9.55	36.69 ± 9.61	5.83 ± 6.06†‖
	BSQ¼	34.71 ± 6.02	35.36 ± 4.88	2.68 ± 7.75
	C	30.84 ± 5.83	30.84 ± 4.12	1.38 ± 9.51

*CMJ = countermovement jump; SJ = squat jump; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant difference pre to post ($p \leq 0.05$).
‡Significant group differences ($p \leq 0.05$); group FSQ, BSQ > C.
§Significant group differences ($p \leq 0.05$); group FSQ, BSQ > BSQ¼.
‖Significant group differences ($p \leq 0.05$); group FSQ, BSQ > C.

with self-selected width of the feet, flexed their knees to reach the deep squat position with proper form (breaking parallel) and returned to starting position. Attempts failed when the subjects (a) rounded their back, (b) lost the bar, (c) were not able to keep their elbows in parallel position to the ground, (d) or where not able to flex the knees to the desired and maximal possible depth. Determination of 1RM was fulfilled within a maximum of 5 trials. Rest between attempts was 5 minutes at least.

After a minimum 5-minute rest, the subjects carried out quarter back squats to 120° of knee extension. To achieve the required movement range in the knee joint, the subjects carried a goniometer on their right knee. Increases of weight loads to determine the 1RM in quarter squats was canceled when the subjects were not able to stabilize the bar with their back. Determination of 1RM was fulfilled within a maximum of 5 trials. Rest between attempts was 5 minutes at least. The investigators supervised the movement range of all the groups during each squat test. According to O'Bryant et al. (75), test-retest reliability of dynamic maximal strength tests in the parallel back squat is $r = 0.93$.

Vertical Jump Performance Testing. Four days after pretest II, the subjects underwent a familiarization test (pretest III) in vertical jumps (CMJ, SJ) and isometric strength testing (MVC, MRFD), followed by pretest IV 3 days later with the same tests. Jumping height was calculated by flight time on a Kistler platform (59). In the CMJ, the subjects started in an erect position, keeping their hands on the hips. The subjects were instructed to quickly squat down to a self-selected depth by keeping a preferably erect posture of the torso. During the eccentric-concentric transition phase, the subjects had to initiate the concentric part with maximal-explosive effort and to jump for maximal height. During flight phase and landing, knees and hips had to be kept extended and toes elevated. The subjects committed as many trials as they were able to enhance their best trials or to confirm these (reliability $r = 0.939$, $p \leq 0.000$).

TABLE 5. Mean values, *SD*s, and percentage changes of maximal dynamic strength in deep front squat of all groups from pretest to posttest.*

		Mean ± *SD*		
Variable	Group	Pretest	Posttest	Change (%)
1RM (kg)	FSQ	73.00 ± 26.48	90.88 ± 25.61	29.12 ± 19.87†‡§
Deep	BSQ	67.00 ± 26.77	80.50 ± 24.97	25.35 ± 20.54†‡§
Front	BSQ¼	72.90 ± 19.95	72.37 ± 21.24	−0.35 ± 11.74
Squat	C	65.00 ± 17.42	65.63 ± 18.34	0.64 ± 08.70

*1RM = 1-repetition maximum; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant difference pre to post ($p \leq 0.05$).
‡Significant group differences ($p \leq 0.05$); group FSQ, BSQ > C.
§Significant group differences ($p \leq 0.05$); group FSQ, BSQ > BSQ¼.

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Table 6. Mean values, *SD*s, and percentage changes of maximal dynamic strength in deep back squat of all groups from pretest to posttest.*

Variable	Group	Mean ± *SD*		
		Pretest	Posttest	Change (%)
1RM (kg)	FSQ	83.50 ± 29.20	98.50 ± 28.75	20.94 ± 11.26†‡§
Deep	BSQ	80.25 ± 30.28	101.50 ± 30.00	30.43 ± 14.99†‡§‖
Back	BSQ¼	87.11 ± 26.05	82.63 ± 26.27	−5.07 ± 7.57†
Squat	C	75.63 ± 23.94	75.94 ± 20.99	1.70 ± 8.18¶

*1RM = 1-repetition maximum; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant difference pre to post ($p \leq 0.05$).
‡Significant group differences ($p \leq 0.05$); group FSQ, BSQ > C.
§Significant group differences ($p \leq 0.05$); group FSQ, BSQ > BSQ¼.
‖Significant group differences ($p \leq 0.05$); group BSQ > FSQ.
¶Significant group differences ($p \leq 0.05$); group C > BSQ¼.

The SJ was initiated at a knee and hip angle of 90° under elimination of any countermovement. The subjects initiated the concentric part on command with maximal-explosive effort and jumped for maximal height. During flight phase and landing, knees and hips had to be kept extended and toes elevated. The subjects committed as many trials as they were able to enhance their best trials or to confirm these (reliability $r = 0.943$, $p \leq 0.000$).

Testing of Isometric Force-Time Parameters. The MVC and MRFD were recorded in the unilateral isometric leg press. The subjects sat in a vertical seat with a knee angle of 120° of knee extension. They were instructed to develop force as explosively as possible on command and to hold the MVC for 3 seconds. The subjects committed as many trials as they were able to enhance their best trials or to confirm these. The maximal RFD (MRFD) is defined as the maximal slope of the recorded force-time curve. Test-retest reliability for MVC left leg was $r = 0.853$ ($p \leq 0.01$) and right leg $r = 0.821$ ($p \leq 0.01$). Test-retest reliability for MRFD left leg was $r = 0.854$ ($p \leq 0.01$) and right leg $r = 0.793$ ($p \leq 0.01$). Rest between attempts was 5 minutes.

Statistical Analyses

The best trials of 1RM in each squat variant, vertical jump height in SJ and CMJ, isometric force-time parameters of MVC and MRFD were recorded and analyzed. First, the Shapiro-Wilk normality test was used to quantify the deviation of the actual data, and its distribution from a Gaussian distribution. Homogeneity of variance was proved with the Levene test. Test requirements were fulfilled at a significance level of $p \leq 0.05$. Pretraining values of the 4 groups were

Table 7. Mean values, *SD*s, and percentage changes of maximal dynamic strength in quarter back squat of all groups from pretest to posttest.*

Variable	Group	Mean ± *SD*		
		Pretest	Posttest	Change (%)
1RM (kg)	FSQ	213.16 ± 62.90	234.21 ± 59.84	13.31 ± 21.16†‡
Quarter	BSQ	179.47 ± 50.49	224.74 ± 44.89	30.59 ± 28.00†§‖
Back	BSQ¼	220.00 ± 42.16	297.89 ± 41.58	37.50 ± 17.19†¶
Squat	C	185.63 ± 40.33	189.38 ± 40.90	2.26 ± 6.28

*1RM = 1-repetition maximum; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant difference pre to post ($p \leq 0.05$).
‡Significant group differences ($p \leq 0.05$); group FSQ > C.
§Significant group differences ($p \leq 0.05$); group BSQ > FSQ.
‖Significant group differences ($p \leq 0.05$); group BSQ > C.
¶Significant group differences ($p \leq 0.05$); group BSQ¼ > FSQ, BSQ, C.

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Table 8. Mean values, *SD*s, and percentage changes of isometric maximal voluntary contraction of all groups from pretest to posttest.*

Variable	Group	Mean ± SD		
		Pretest	Posttest	Change (%)
MVC left (N)	FSQ	2,275 ± 628	2,256 ± 538	1.05 ± 15.06†‡
	BSQ	2,056 ± 551	2,011 ± 472	−0.58 ± 15.17†‡
	BSQ¼	2,549 ± 467	2,193 ± 440	−13.34 ± 12.21§
	C	2,013 ± 413	1,723 ± 324	−13.89 ± 8.85§
MVC right (N)	FSQ	2,248 ± 439	2,226 ± 444	−0.21 ± 12.91‖¶
	BSQ	2,135 ± 499	2,086 ± 450	−1.45 ± 10.23‖¶
	BSQ¼	2,489 ± 404	2,239 ± 372	−9.59 ± 9.57§
	C	2,139 ± 373	1,844 ± 348	−13.54 ± 10.47§

*MVC = maximal voluntary contraction; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant group differences in left leg ($p \le 0.05$), group FSQ, BSQ > C. ‡Significant group differences in left leg ($p \le 0.05$); group FSQ, BSQ > BSQ¼.
§Significant difference pre to post ($p \le 0.05$). ‖Significant group differences in right leg ($p \le 0.05$); group FSQ, BSQ > C.
¶Significant group differences in right leg ($p \le 0.05$); group FSQ, BSQ > BSQ¼.

tested for a significant difference using a 1-way ANOVA ($p \le 0.05$). Comparison of group and test time of the dependent variables was run by a 2-way ANOVA for assessing main effects and interactions. This was provided with a *pairwise comparison* of all the groups. If significant effects for the factor test time occurred, the Scheffé test was applied post hoc ($p \le 0.05$).

Results

All the results of the main effects and interaction effects (group × time) are based on absolute changes (2-way ANOVA). Additionally, percentage changes are displayed.

Changes in the body mass were not significant for group BSQ¼ and C. Group FSQ showed significant increases from 71.02 ± 14.07 to 71.78 ± 13.58 kg ($p \le 0.05$) and group BSQ from 71.55 ± 12.34 to 72.32 ± 12.21 kg ($p \le 0.05$). There were no statistical interaction effects between the 4 groups.

Development of Vertical Jump Performance in Squat Jump and Countermovement Jump

Both group FSQ and group BSQ attained significant increases of vertical jump performance in CMJ ($p \le 0.05$) and SJ ($p \le 0.05$). Similar to group C, group BSQ¼ showed no

Table 9. Mean values, *SD*s, and percentage changes of isometric maximal rate of force development of all groups from pretest to posttest.*

Variable	Group	Mean ± *SD*		
		Pretest	Posttest	Change (%)
MRFD left ($N \cdot ms^{-1}$)	FSQ	11.01 ± 2.85	10.58 ± 2.61	−2.50 ± 16.22†
	BSQ	11.20 ± 2.40	10.66 ± 2.28	−4.35 ± 12.06†
	BSQ¼	12.67 ± 2.49	10.47 ± 2.22	−16.88 ± 11.70‡
	C	11.11 ± 2.13	10.14 ± 1.79	−8.10 ± 9.15†‡
MRFD right ($N \cdot ms^{-1}$)	FSQ	11.22 ± 2.79	10.46 ± 2.31	−5.25 ± 15.04‡§
	BSQ	11.67 ± 2.15	11.09 ± 1.93	−4.30 ± 11.16§
	BSQ¼	12.25 ± 2.43	10.42 ± 1.88	−14.23 ± 7.54‡
	C	11.94 ± 2.34	10.36 ± 1.75	−12.02 ± 12.84

*MRFD = maximal rate of force development; group FSQ = deep front squat ($n = 20$); group BSQ = deep back squat ($n = 20$); group BSQ¼ = quarter back squat ($n = 19$); group C = control ($n = 16$).
†Significant group differences in left leg ($p \le 0.05$); group FSQ, BSQ, C > BSQ¼.
‡Significant difference pre to post ($p \le 0.05$).
§Significant group differences in right leg ($p \le 0.05$); group FSQ, BSQ > BSQ¼.

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statistically significant changes of vertical jump performance in both jump types (Table 4).

Group × time comparisons of vertical jump performance in CMJ (Table 4) demonstrated significantly higher jumping heights for group FSQ and group BSQ over group C ($p \leq 0.05$) and group BSQ¼ ($p \leq 0.05$). There were no significant differences between group FSQ and group BSQ ($p = 0.852$). Likewise, the comparison between group C and group BSQ¼ did not elicit any statistical difference (group × time $p = 0.560$).

Group × time comparisons of vertical jump performance in SJ (Table 4) produced both for group FSQ and group BSQ significantly higher SJ scores over group C ($p \leq 0.05$). For interaction effects, group BSQ¼ did not offer any statistically significant difference to group C ($p = 0.497$). Group BSQ did not feature any statistically significant difference to group BSQ¼ (group × time, $p = 0.116$) in SJ performance, whereas group FSQ showed a trend toward higher SJ values over group BSQ¼ (group × time, $p = 0.052$). Vertical jump performance in the SJ did not provide any statistical difference between group FSQ and group BSQ ($p = 0.626$).

Development of Dynamic Maximal Strength (1RM) of Deep Front Squats

Training of group FSQ and BSQ induced significant enhancements of 1RM ($p \leq 0.05$) of deep front squats. Neither group C nor group BSQ¼ demonstrated any statistically significant changes (Table 5).

Comparisons of interaction effects in 1RM of the deep front squat (Table 5) showed for both group FSQ and group BSQ significantly higher dynamic maximal strength values than for group C ($p \leq 0.05$) and group BSQ¼ ($p \leq 0.05$). Group BSQ¼ did not have any statistical difference compared with group C (group × time, $p = 0.604$). There was no significant difference between group FSQ and group BSQ ($p = 0.090$), although a trend toward higher 1RM for group FSQ was seen.

Development of Dynamic Maximal Strength (1RM) in Deep and Quarter Back Squats

Training of both group FSQ and group BSQ produced significant increases in 1RM of deep back squats ($p \leq 0.05$) (Table 6) and 1RM of quarter back squats ($p \leq 0.05$) (Table 7). Group BSQ¼ demonstrated significant elevations in 1RM of *quarter* back squats ($p \leq 0.05$) (Table 7), this group showed significant declines in 1RM of *deep* back squats ($p \leq 0.05$) (Table 6). Group C did not show any statistical changes in 1RM of both squat variants.

Group × time comparisons of 1RM in deep back squats (Table 6) demonstrated both for group FSQ and group BSQ significantly higher dynamic maximal strength scores than group C ($p \leq 0.05$) and group BSQ¼ ($p \leq 0.05$). The significant declines of 1RM in deep back squats of group BSQ¼ ($p \leq 0.05$) led to significantly lower dynamic maximal strength values in the posttest compared with group C (group × time, $p \leq 0.05$). The development of 1RM in deep back squats resulted in significantly higher dynamic maximal strength values of group BSQ over group FSQ (group × time, $p \leq 0.05$).

Group × time comparisons of 1RM in quarter back squats (Table 7) revealed that group BSQ¼ showed significantly higher dynamic maximal strength scores than group BSQ ($p \leq 0.05$), group FSQ ($p \leq 0.05$), and group C ($p \leq 0.05$). Group BSQ gained significantly more in the 1RM of quarter back squats than group FSQ (group × time, $p \leq 0.05$) and group C (group × time, $p \leq 0.05$). Group FSQ demonstrated significantly higher dynamic maximal strength values than group C ($p \leq 0.05$).

The strongest subject moved a weight load of 380 kg in the pretest of quarter back squat, which was the maximum possible weight load of this test apparatus. The subject was able to maintain a straight back and did not feel maximally stressed. This subject was a participant of group BSQ and was not tested in 1RM quarter back squat in the posttest. Hence, there were only 19 of the 20 available subjects of group BSQ, who were posttested in 1RM quarter back squat.

A female participant of group FSQ was not able to execute 1RM quarter back squat in posttest because of backache. Thus, only 19 of the 20 available subjects of group FSQ participated in posttesting of 1RM quarter back squat.

Development of Maximal Voluntary Contraction

In posttests (Table 8), groups FSQ and BSQ showed no statistically significant changes of the unilateral MVC. Both group C and group BSQ¼ demonstrated significant declines of MVC in the left leg ($p \leq 0.05$) and significant declines of MVC in the right leg ($p \leq 0.05$).

Group × time comparisons of MVC in the left and right legs revealed (Table 8) that there were no statistically significant differences between group FSQ and BSQ ($p = 0.787$ and $p = 0.862$). Posttest showed for group FSQ that there were significantly higher values of MVC both for left and right legs compared with that in group C (group × time, $p \leq 0.05$) and group BSQ¼ (group × time, $p \leq 0.05$). These interaction effects in superior isometric maximal strength were also shown for group BSQ in left and right legs over group C ($p \leq 0.05$) and over group BSQ¼ ($p \leq 0.05$). There were no interaction effects for MVC of the left leg ($p = 0.482$) and right leg ($p = 0.628$) between group BSQ¼ and group C.

Development of Maximal Rate of Force Development

Development of the unilateral isometric testing confirmed declines in MRFD of all 4 groups (Table 9). These reductions of the right and left legs were significant for group BSQ¼ ($p \leq 0.05$) and significant for group C ($p \leq 0.05$). Although group BSQ did not confirm any statistically significant declines, group FSQ showed a significant decrease only in the right leg ($p \leq 0.05$).

Group Differences in the Posttest of Maximal Rate of Force Development Table 9 demonstrates significantly higher explosive strength values of group FSQ compared with group BSQ¼ (MRFD left $p \leq 0.05$, MRFD right $p \leq 0.05$). These

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interaction effects were also found for group BSQ, which had significantly higher explosive strength scores in the MRFD of left ($p \leq 0.05$) and right leg ($p \leq 0.05$) in contrast to group BSQ¼. There were no interaction effects for the MRFD between group FSQ and BSQ (MRFD left $p = 0.821$, MRFD right $p = 0.694$). Group differences to group C revealed no interaction effects neither for group FSQ (MRFD left $p = 0.320$, MRFD right $p = 0.151$) nor for group BSQ (MRFD left $p = 0.334$, MRFD right $p = 0.700$). Although there was no group difference between group BSQ¼ and group C in MRFD of the right leg ($p = 0.626$), measurements of MRFD in the left leg demonstrated significantly lower explosive strength values of group BSQ¼ compared with group C ($p \leq 0.05$).

Discussion

Training induced significant ($p \leq 0.05$) elevations in 1RM of the specific squat variant that the subjects had to perform in each experimental group. This development of 1RM is consistent with previous research findings of a general strength training with a strength-power periodization in the closed-kinetic chain (7,60,75,81,94,102,111). The subjects of group C were not allowed to perform any strength training exercises for the lower extremities during the intervention. Control subjects were still able to participate in their physical education classes only. As expected, developments of dynamic maximal strength and vertical jump performance did not show any significant alterations. The significant declines of MVC and MRFD may be explained by a lack of motivation.

The research questions can be answered as follows: (I) Periodized maximal strength training in quarter squats elicited significant higher angle-specific increases of 1RM compared with periodized maximal strength training in deep front and back squats. (II) Quarter squat training did not produce any significant changes in vertical jump performance and (III) did not develop any increases in MRFD and MVC in the trained joint angle. Instead quarter squat training elicited significant declines in both isometric force-time parameters.

Group BSQ¼ showed significant ($37.50 \pm 17.19\%$, $p \leq 0.05$) elevations of 1RM in quarter back squats, which were the highest percent changes in dynamic maximal strength of all groups. As expected, the absolute strength gains were significantly higher than these of the other groups. Likewise, Graves et al. (37) demonstrated the highest gains in training loads within the training amplitude for these subjects, who performed dynamic leg extensions in the activity range with maximal strength developing potential (120–180° knee extension).

Adaptations of group BSQ¼ were limited to 1RM of their specific range of motion and were not accompanied by any improvements in the deep front and back squat. These results can be confirmed by Weiss et al. (105): The training group, which performed quarter back squats, did not show significant transfer effects of 1RM to parallel back squats after training and demonstrated significant lower dynamic maximal strength values ($p \leq 0.05$) than the training group that carried out parallel back squats.

For group BSQ¼, posttesting of 1RM in *deep back squats* demonstrated significant reductions ($-5.07 \pm 7.57\%$, $p \leq 0.05$) and no statistically significant changes in the 1RM of *deep front squats* ($-0.35 \pm 11.74\%$). Although posttest of 1RM in the front squats did not show any interaction effects between group BSQ¼ and group C ($p = 0.604$), there was a significantly lower 1RM in *deep back squats* of group BSQ¼ compared with group C (group × time, $p \leq 0.05$). Group BSQ¼ was not able to transfer the accentuated maximal strength potential into the deep knee positions of the demanding coordination sequence of front and back squats.

Although group BSQ¼ demonstrated the highest strength gains in their specific squat variant, accompanied by significant group differences ($p \leq 0.05$) over group BSQ, FSQ, and C, there were no significant transfer effects into the acceleration process of SJ and CMJ performances. Posttests in the SJ performance of group BSQ¼ were marked by no statistically significant changes ($2.68 \pm 7.75\%$). There was no interaction effect to group C ($p = 0.497$). Furthermore, group BSQ¼ showed no statistically significant changes in CMJ heights ($-0.01 \pm 6.77\%$), nor interaction effects of CMJ performance to group C ($p = 0.560$). These developments of speed-strength performances are contradictory to the findings of Wilson et al. (110): After a 10-week general strength training with high weight loads in machine based quarter squats (120°) (plyometric power system), the subjects with "strength training experience" of at least 1 year showed significant elevations in vertical jump heights of SJ ($6.8 \pm 4.9\%$, $p \leq 0.05$) and CMJ ($5.1 \pm 7.5\%$, $p \leq 0.05$). Entry requirement for their study was a dynamic maximal strength level in quarter squats that was higher than bodyweight. This is a very imprecise description that does not allow any estimation of the subjects' training status. The present findings confirm, that the female subjects ($n = 23$) of all 3 experimental groups, predominantly unfamiliar with strength training, were able to squat 2.49 times of their own bodyweight in the pretest of quarter back squat. The informative value of these findings, published by Wilson et al. (110), has to be regarded with severe restriction and can probably be applied to male subjects with a very low training level. Although the subjects of group BSQ¼ did not train with free weights, there was no restriction in the horizontal movement plane compared with the plyometric power system of the Wilson study (110). The subjects studied by Wilson et al. (110) performed the vertical jumps in the plyometric power system, too. The subjects had the opportunity to jump without any motion restriction, which offers a higher generality and practical transferability of the results for vertical jumps, as they occur in sports activities.

The results of group BSQ¼ are in conflict with the data of Clark et al. (20). After 5 weeks of strength training in the bench press, which was performed in the full range of motion and in several partial amplitudes, significantly higher speed-strength

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performances in bench press throw occurred compared with pure full range of motion training. These findings are not based on angle-specific adaptations but on different exploited activity areas of the involved agonists. With rising extension of the elbow, the m. triceps brachii reaches higher strength developing conditions (27), which cannot be used within a full range of motion training. Angle-specific bench pressing with comparatively supramaximal loads exploited accordant strength deficits of the activity range of the triceps, which consists of a high adaptation potential with rising elbow extension. However, this cannot be transferred into the quarter squat. With the same load configuration of the deep squat, the subjects of group BSQ¼ were endangered to collapse at their thoracic spine during training and testing, before the extension strength of m. quadriceps femoris could become the limiting factor. In pretests of 1RM, group BSQ¼ was able to move weight loads in quarter back squats, which were 2.8 ($\pm$1.2) times higher than 1RM of deep back squats and 3.2 ($\pm$0.75) times higher than 1RM of deep front squats. In posttests, these ratios increased to highly significant magnitudes of 4.02 ($\pm$1.59) times ($p = 0.000$) and 4.38 ($\pm$1.02) times ($p = 0.000$). Table 3 shows the relative strength values of all the groups, too. Although the subjects trained with very high weight loads, these were not heavy enough to induce effectual training stimuli on knee and hip extensors within the *small movement range* of knee and hip joints. This interpretation is supported by the development of MVC and MRFD in group BSQ¼. According to the findings of angle-specific isometric strength training, the highest gains of MVC are to be expected in the trained joint angle (10,32,58,64,70,96,104). The isometric testing angle matched the training angle of the turning point in the quarter squat. Based on the findings of Hoff and Helgerud (50) and Young and Bilby (117), this should cause significant increases of MVC and MRFD due to an angle-specific transfer effect. But this transfer effect cannot be confirmed by the present results. Posttests showed significant declines of MVC and MRFD in the left leg (MVC left: $-13.34 \pm 12.21\%$, $p \le 0.05$; MRFD left: $-16.88 \pm 11.70\%$, $p \le 0.05$) and significant declines of MVC and MRFD in the right leg (MVC right: $-9.59 \pm 9.57\%$, $p \le 0.05$; MRFD right: $-14.23 \pm 7.54\%$, $p \le 0.05$). Although there was no group difference between group BSQ¼ and group C in the MRFD of the right leg ($p = 0.626$), measurements of MRFD in the left leg demonstrated significantly lower explosive strength values of group BSQ¼ compared with that in group C ($p = 0.027$). Comparing group differences, posttest results of group BSQ¼ showed significantly lower values of MVC and MRFD in the *left and right legs* compared with group FSQ ($p \le 0.05$) and group BSQ ($p \le 0.05$). Furthermore, the development of MVC in both legs revealed that group BSQ¼ showed the same group differences as group C did.

These data approve the aforementioned interpretation that the training progress of group BSQ¼ rested on the high stabilization requirements of the high weight loads.

The obtained development of MVC is in conflict with the findings of Wilson et al. (110). After 5 weeks of strength training in quarter squats, these authors determined significant gains in MVC. After strength training in the half squat (90°), Hoff and Helgerud (50) and Young and Bilby (117) determined significant elevations of MVC and MRFD at 90 and 100° knee angle. However, the isometric testing condition in all 3 studies was performed *bilateral* and in another posture (isometric squat). Apparently, the greater conformity between the dynamic training exercise and the isometric testing condition was 1 deciding factor for these results of measurement. In consideration of the isometric test results of group FSQ and BSQ, the significant declines of the isometric force-time parameters of group BSQ¼ cannot be solely explained by the different strength action (bilateral vs. unilateral) and the lower conformity to the testing apparatus. During isometric strength testing, no EMG measurements were performed, because this was beyond the scope of this study. Therefore, it is not possible to evaluate if an altered neuromuscular activation of the leg extensors (with increased cocontraction of the hamstrings) occurred. Maybe a reduced motivation of the subjects of group BSQ¼ has to be considered.

Posttest of deep front squats revealed significant increases both for group FSQ ($29.12 \pm 19.87\%$, $p \le 0.05$) and group BSQ ($25.35 \pm 20.54\%$, $p \le 0.05$). Group BSQ had the ability to transfer its specific elevated dynamic maximal strength level into the motion sequence of deep front squats. For both groups that performed deep squats, the percent gains in 1RM front squats occurred in comparatively equal magnitude. This certifies a high conformity in motion quality between deep front and deep back squat.

Group FSQ and group BSQ were able to implement their specific elevated dynamic maximal strength level into the motion sequence of the other deep squat variant, which occurred to a significant extent ($p \le 0.05$). This issue argues for the findings of Gullett et al. (38) in the conformity of the recruited muscle groups between front squats and back squats. For a successful lift, the correct execution of front squats is connected to the strict maintenance in torso erection of the thoracic spine and the horizontal conversion position of the elbows (31). Trunk stabilization and technique execution required a lower training load of group FSQ. This could be an explanation for the interaction effects in posttest of 1RM deep back squats between group FSQ and group BSQ, which showed lower dynamic maximal strength scores of group FSQ compared with group BSQ ($p \le 0.05$).

Indeed, group FSQ demonstrated significant increases of 1RM of quarter back squats in posttest ($13.31 \pm 21.16\%$, $p \le 0.05$). But this group showed the lowest elevations for this test: Group differences were marked by significantly higher 1RM of group BSQ ($p \le 0.05$) and group BSQ¼ ($p \le 0.05$) compared with group FSQ. At least for group FSQ, the significant increases ($p \le 0.05$) of 1RM in quarter back squats

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of the posttest offered significantly higher dynamic maximal strength values than group C ($p \le 0.05$). This indicates higher trunk stability as a result of the 10-week strength training in deep front squats.

Video analyses of experienced weightlifters and powerlifters revealed that the parallel position in both front squats and back squats (high bar) result in nearly equal knee angles (31). The published EMG data of Gullett et al. (38) proved no significant differences in the magnitude of activity of m. biceps femoris, rectus femoris, semitendinosus, vastus lateralis, and medialis including m. erector spinae between both exercises with submaximal loads (3 repetitions with 70% 1RM), although front squats were performed with lighter loads (back squat 90% BW, 61.8 ± 18.6 kg; front squat 70% BW, 48.5 ± 14.1 kg) (38). Compared with front squats, it can generally be assumed that the completion of parallel back squats (high bar) is characterized by higher hip flexion (31), whereby torque values in hips are considerably higher than those in the knees (13,69). Lander et al. (63) determined 5 male subjects with strength training experience in performing parallel back squats (75–80% 1RM) with an 8RM load. Completion near muscular failure additionally caused greater hip flexion, induced by exhaustion. Compared with front squats, the intermuscular coordination sequence in back squats emphasizes hip and back extensors, allowing higher training loads because of a more advantageous moment arm. This explains that group BSQ gained significantly more in the 1RM of quarter back squats than did group FSQ (group × time, $p = 0.030$) and showed a higher training-induced percent transfer of dynamic maximal strength into the larger strength developing conditions of quarter back squats (30.59 ± 28.00%, $p \le 0.05$). This supports previous results in which 9 weeks of parallel back squat training provided significant elevations of 1RM in quarter back squats ($p \le 0.05$) (105).

By comparing *percentage differences* in 1RM quarter back squats, group FSQ showed significant lower gains in contrast to group BSQ¼ ($p \le 0.05$). But between group BSQ and BSQ¼, there was no significant group difference in this test ($p = 0.258$). This means, deep back squats–as an "unspecific" exercise (108,118)–guarantee percentage gains in the activity range of 120–180° of knee extension that are almost equal to percentage gains induced by quarter back squats–a supposedly specific exercise (57,108). In addition to the results of the development in vertical jump performance and isometric force production, this seriously questions the necessity of implementing quarter back squats into a general strength training program.

The development of vertical jump performance in the SJ attested group FSQ and group BSQ significant enhancements of 7.19 ± 7.33% ($p \le 0.05$) and 5.83 ± 6.06% ($p \le 0.05$), exhibiting no interaction effects between both groups ($p = 0.626$). Posttest of SJ performance certified for group FSQ and group BSQ in each case, significantly higher SJ scores over group C ($p \le 0.05$). Group BSQ did not succeed any statistically significant difference to group BSQ¼ (group × time, $p = 0.116$) in SJ performance, whereas FSQ showed a trend toward higher SJ heights over group BSQ¼ ($p = 0.052$).

Posttest in the vertical jump performance of CMJ was characterized by statistically equal and significant elevations for group FSQ (8.29 ± 6.15%, $p \le 0.05$) and group BSQ (7.79 ± 5.43%, $p \le 0.05$), without any statistical difference between these 2 groups ($p = 0.852$). Furthermore, these changes of group FSQ and group BSQ resulted, in each case, in significantly higher jumping performances over group C ($p \le 0.05$) and group BSQ¼ ($p \le 0.05$).

According to the best of the authors' knowledge, these effects of general strength training in deep front squats on the development of vertical jump performance are published for the first time. Based on the high conformity of the neural activation of hip and leg extensors in parallel back squats (38), these findings are consistent with the expected and numerous documented performance-enhancing transfer effects of parallel or deep back squat training to speed-strength ability in concentric muscle action (SJ) (40,42,44,80,90,111) and the long SSC (5,7,8,33,40,42,47–49,53,65,90,92,94,95,102,111). Posttests in determining 1RM revealed that group FSQ used weight loads, which were 11.69% lower (10.62 kg) than those of group BSQ (mean values). Group FSQ demonstrated the highest percentage development potential in speed-strength capacity of both types of jumps. Therefore, this exercise provided a more efficient training effect than deep back squats.

The posttests revealed no significant improvements of MVC or MRFD for both deep squat groups. Although significant gains in unilateral MVC could be conducted after bilateral strength training in deep back squats by Baker et al. (8) and Häkkinen and Komi (41), this could not be confirmed for unilateral RFD by previous findings (8,111) and the present results. The subjects were predominantly inexperienced in strength training. Learning the proper form of deep squats demands a much longer time span than does the execution of quarter squats. This results in a higher neuromuscular challenge and greater adaptations in intermuscular coordination in regard to synergistic activation of agonists (83). Häkkinen and Komi (41) determined significant increases of bilateral ($p \le 0.001$) and unilateral MVC ($p \le 0.01$) of the leg extensors after 16 weeks of strength training in deep back squats. The subjects performed different portions of concentric and eccentric contractions. The authors asserted higher enhancements in voluntary activation in the bilateral isometric strength test as in the unilateral test. The findings may originate in different innervations patterns between bilateral and unilateral force production and the observed problem of muscle action specificity (83). It is possible that a longer training duration (39,41,44) and bilateral isometric strength testing would have shown significant increases in MVC (39,41,44,50,117) and MRFD

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(50,117). The significant ($p \leq 0.05$) increases of 1RM in FSQ and BSQ enabled a significant ($p \leq 0.05$) transfer into *the dynamic realization of speed-strength ability* in the SJ and CMJ. Therefore, the missing improvements of the isometric force-time parameters questions the diagnostic relevance of isometric strength testing after eccentric-concentric strength training.

Adaptations in terms of enhanced intermuscular coordination can be assumed for the very high percentage elevations of dynamic maximal strength in the deep squats (83). The final 2 week strength-power phase, which was marked by maximum effort repetitions (86), served for the improvement in intramuscular coordination in regard of faster motor unit recruitment and enhanced firing rates (15,72) with a more synchronized discharge pattern of the α-motoneurones (72). In addition, after 14 weeks of periodized strength training of the lower extremity, Aagaard et al. (1) detected significantly elevated V-wave ($p \leq 0.01$) and H-reflex ($p \leq 0.05$) responses of the plantar flexors, obtained during MVC and electrical stimulation. The authors attribute this to enhanced central motor drive and alterations in presynaptic Ia afferent inhibition and increased excitability of the α-motoneurone pool.

The significant enhancements ($p \leq 0.05$) of speed-strength capacity in the SJ and CMJ of group FSQ and BSQ can therefore be predominantly explained by an enhanced voluntary neuromuscular activation of the hip and knee extensors, without the exclusion of associated morphological adaptations in both hypertrophy phases. The research findings of Raastad et al. (79) suggest that parallel squats provide larger gains in muscle CSA than quarter squats. Hence, greater hypertrophy likely occurred for groups FSQ and BSQ than BSQ¼. In the study carried out by Raastad et al. (79), the experimental group that trained with quarter back squats over 12 weeks, lifted twice the training load compared with the group with parallel back squats. In the quarter squat, the subjects of group BSQ¼ lifted *4 times* the weight of deep front and back squat. According to Wilson (108), this should have led to higher tension stimuli of the leg extensors and hence to a reduction in neural inhibition of hip and knee extensors. The greater angle-specific strength development of the quarter squat is suggested to provide higher transfer effects of force application into the acceleration process of concentric and reactive speed-strength performance than deep squats (108). The present findings for the development of speed-strength performance in concentric muscle action (SJ) and long SSC (CMJ) of group BSQ¼ invalidate this assumption. Also taking the magnetic resonance imaging (MRI) findings of Raastad et al. (79) into account, it can be seen that despite lower training loads (see Tables 3, 5, and 6 of the present results) the muscle fibers of m. quadriceps femoris are exposed to better mechanical and neural stimuli in parallel and deep squats. This explains the superiority of group FSQ and group BSQ in vertical jump performance over group BSQ¼. In the squat exercise, increased challenges of the force development of hip and knee extensors are provided, if the motion reversal is initiated in deep joint positions. Although the weight is limited by the long moment arm in the turning point, the highest peak forces and hence the highest tension stimuli are realized in the motion reversal into the concentric muscle action (62,114). Strength training interventions over 5 weeks in leg extension with eccentric-concentric (88), concentric (12), or eccentric (12) muscle actions confirm significant increments of pennation angle and fascicle length of m. vastus lateralis in untrained subjects. These sonographically analyzed adaptation phenomena (12,88) are explained by additional integration of sarcomeres in parallel and in series. In animal studies, this could be particularly initiated by the stimulus combination of high *passive and active* myofibrillar tensions (35). Because this initiating stimulus combination dominates in deep joint positions on hip and knee extensors, it can be assumed that correspondent increases of muscle fiber length occur besides increases of muscle CSA. A longer muscle and a longer muscle fiber contract faster because of the serially greater number of possible crossbridges per time, respectively (26,35). Coupled with a greater CSA, this will have a positive effect on the *force development per time* (RFD) in the long run.

Adaptations in intermuscular coordination of group BSQ¼ may have been minimal because of the comparable small movement amplitude. The execution of quarter squats was subject of distinct isometric stabilization activity of the trunk, which limited the extent of the training loads and did not allow stress exceeding threshold levels to the hip and knee extensors. In regard to neural and morphological adaptations of group BSQ¼, the back extensor was responsible for the highest gains in dynamic maximal strength of the specific training exercise, which were marked by significant interaction effects over the other 3 groups. Within the small motion amplitude, it was impossible to develop the necessary neural stimulus pattern of hip and knee extensors to enhance the dynamic speed-strength behavior in concentric muscle action and in the long SSC.

Practical Applications

According to Zatsiorsky and Kraemer (118), maximizing speed-strength performance in the long SSC is not imperatively linked to an increased acceleration amplitude. “Volleyball players almost never jump for height from deep squats” ([118], p. 123). At least, this is the case in conditions when a successful ball control depends on a preferably fast reaction, where the acceleration process is limited to low squat depths in favor of a rapid execution. According to Wilson (108) and Zatsiorsky and Kraemer (118), if peak force is realized during a short segment of the movement amplitude, there should be no necessity of training the maximal strength over the whole range of motion. This line of argument is not conclusive. To achieve a maximal vertical

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jump height in conditions of time restriction, it should also be preferred to elevate or to optimize the acceleration distance through a modified jump technique. To avoid an elevation in execution time, impulse size can be influenced through modifications of the acceleration sequence (fast eccentric phase, minimization of transition time from eccentric to concentric muscle action, maximization of RFD, optimization of impulse duration) (21–23,97). These parameters are modifiable. Twelve weeks of jump squat training can produce higher acceleration distances through deeper execution of the CMJ (21). This increase in performance was not associated with a change in eccentric, concentric, and hence absolute execution time. According to Cormie et al. (21), the significant elevations in jump height ($p \leq 0.05$) are the result of higher stretch velocities in the eccentric-concentric transition phase, which may be responsible for the enhanced concentric performance potentiation in regard to elevated RFD ($p \leq 0.05$), increased peak power ($p \leq 0.05$) and peak velocity ($p \leq 0.05$). It is not meaningful to limit the acceleration distance to small squatting depths in favor of a preferable fast execution. Correspondent training methods should aim at enhancing the aforementioned parameters that have an influence on increasing impulse size within a given timeframe. The postulation of Zatsiorsky and Kraemer (118) to limit the range of motion within a general strength training exercise to conform with the competition movement does not achieve this purpose. Based on the present findings, quarter squats are an inappropriate exercise to enhance vertical jump performance. Although the present research project involved moderately trained physical education students, the obtained findings make the use of quarter squats in elite athletes questionable. A lower training status should have been advantageous for neural transfer effects in the quarter squat, which did not occur. The primary objective of general strength training in speed-strength events constitutes an enhancement of single speed-strength action, with which high training intensities are necessary (86). It is required that the strength training exercises are performed in joint angular regions, in that the desired muscle groups are confronted with an appropriate tension stimulus. The elevated force development, which is gained through deep or parallel squats, is not only available in the initial concentric phase of the turning point, but it also has a positive effect on speed-strength performance in all other knee joint angles (49) and, according to Weiss et al. (105) and the gathered data, on dynamic maximal strength behavior in knee joint angles of the quarter squat. The transfer of the gained dynamic maximal strength level into sports-specific motion sequences is achieved through concomitant technique training. Provided that the motion sequence of the competition movement does not allow any elevation of acceleration distance in the knee joint and is restricted to high degrees of extension (i.e., sprint), technique training becomes more important. The specific neural activation of the muscle, which is necessary to produce peak forces in high degrees of knee extension, should always be developed through sprint and jump exercises of the competition movement. In regard to the achieved angular velocities, only these conditions are to be considered as specific (14). Based on functional aspects, only a deep squat can be used as an effective general strength training exercise. Solely, deep joint positions provide the required neural and morphological stimuli for the hip and knee extensors to positively influence the acceleration process. In competition phases, deep squats can help sustain dynamic maximal strength levels and should therefore rarely be excluded from a strength training program. By concomitant use of technique training, maintaining maximal strength levels allows the safe handling of high relative and absolute loads (speed-strength methods). This combination of heavy and ballistic strength training exercises allows higher transfer effects to reactive speed-strength performances (6,93). Periodized maximal strength training in quarter squats elicits significant transfer losses into the isometric maximal and explosive strength behavior of hip and knee extensors in the initial phase of the turning point and does not provide any significant increments of force application into the acceleration process of reactive and concentric speed-strength performances. This refutes the in training practice assumed basic concept of superior angle-specific transfer effects. With the same load configuration as in deep squats, the comparatively supramaximal loads in the quarter squat overstrain the stabilization possibilities of the thoracic spine. Therefore, the thoracic spine is exposed to an increased danger of impairing shear and compressive forces. These factors lead to a higher risk of injury in this squat variant. Cappozzo et al. (16) computed the compressive forces on the L3–L4 segment on 4 subjects (57–82 kg) who performed half and quarter back squats. Weights between 0.8 and 1.6 times body weight resulted in compressive forces of 6–10 times of the body weight in the motion reversal of the squat. It can be assumed that the measured relative strength values in deep front and back squats of group FSQ and BSQ produced compressive forces of the lumbar spine, which were within previously calculated values (16). With increasing loads, a linear increase in compressive forces on the vertebral bodies (16) and hence in intradiscal pressure of the intervertebral discs occurs (61). Relative strength values in the quarter squat of group BSQ¼ were on average 3.89 times bodyweight. Taking the calculations of Cappozzo et al. (16) into account, compressive forces acting on the L3–L4 segment may have exceeded 20 times of the body weight. Performing the squat until failure with high loads involves the risk of forward leaning (63) and ventral flexion (68). Ventral flexion causes diminished activity of the m. erector spinae (67,78) and reduced contact area of the apophyseal joints (78,85). This leads to increased tensile forces on ligaments (67,78) and shear forces on

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intervertebral discs (78,85). Vertebral bodies, and hence intervertebral discs, can functionally adapt to high axial compressive forces in the long run ([30], pp. 263). However, high compressive loads in ventral flexion increase the risk of a spinal discus prolapse (2). The results of group BSQ¼ in posttest ($n = 19$) demonstrate for the quarter squat that the subjects were able to lift 4.38 (±1.02) times the weight of the deep back squat, although the majority of the subjects had low strength training experience. *Well-trained athletes are able to lift much higher weights.* Transferred to the weight of the deep back squat (250 kg, 2.27 times BW), which was lifted by a powerlifter in a study of Nisell and Ekholm (74), this weight would correspond to utopian 1,005 kg. In training practice, this weight is out of question, because such a high barbell load is unlikely to be stabilized by the back musculature. Its not the legs that would be performance limiting but the back, which enables no training effect for the legs. According to Escamilla (28), within the first 50° of knee flexion, the lowest patellofemoral compressive forces can be expected. This is based on calculations on knee joint forces, which were assessed in the half squat (29). These scores cannot be readily transferred into the quarter squat because (a) the influence of reversal of motion (with minor tendofemoral support surface and lower retropatellar contact zones) and (b) the different barbell loads of the particular squat variant are not taken into account. The calculated force values in half squats by Escamilla et al. (29), which are meant to be transferred into lower extension angles until 120°, are quoted too low. The highest dynamic peak forces occur after the change into the concentric muscle action (62,114). Considering the present relative strength values in the quarter squat of group BSQ¼ of 3.89 times BW, the tibiofemoral and patellofemoral compressive forces in the turning point are much higher, respectively, with a higher risk of injury of passive tissues. Higher weights result in elevated tibiofemoral (82) and patellofemoral compressive forces (103). Knee angles up to 120° are characterized by low tendofemoral support surface (9,45) and lower retropatellar contact zones (25,45). But with rising flexion, a cranial displacement of facet contact areas with continuous enlargement of the retropatellar articulating surface arises (to 60°: 25, to 40°: 45). Additionally, with increasing flexion, the cumulative contact between quadriceps tendon and intercondylar notch as tendofemoral support surface ("wrapping effect," 9, p. 24) contributes to an enhanced load distribution and enhanced force transfer with reduced retropatellar compressive force (calculation to 60°: 73, to 50°: 9; to 40°: 45). Thus, lower risks of injury may be expected in deep joint positions. For performance athletes, the perennial training structure of general strength training in deep front and back squats obtains target values between 1.5 and 2 times bodyweight (113). Because in deep squat lower weights are used and regular practiced strength training leads to functional accommodations of the passive tissue ([30], pp. 263), concerns of degenerative changes of the tendofemoral complex in deep squats (28) are unfounded. Measurements of articulating contact areas of the menisci approve decreases with rising flexion (3). However, rising compressive loads provoked enlargements of the articulating contact zone. These ex vivo measurements were carried out to 90° flexion only (3). In addition, cartilage deformation zones of the tibia plateau demonstrate continuous enlargements with rising knee flexion in vivo (BW lunge), analyzed with MRI to 60° (11). The influence of soft tissue contact between the back of thigh and calf plays a major role in reducing the knee joint forces past 40° of knee extension (34,120). Although these joint angles are not performed in the deep squat exercise, this soft tissue contact can begin at higher degrees of extension (from ~50°) (120) and depends on the muscle CSA of the hamstring and the calf muscles. Declines of tibiofemoral (34,120) and patellofemoral compressive forces (34) may therefore result in the deep squat. It remains unclear which structures of the knee (such as menisci and ligaments) benefit from soft tissue contact. For the above reasons, the apparent higher risk for degenerative changes such as osteochondrosis dissecans of the oddfacett in deep squats, as suggested by Escamilla (28), seems unfounded and is unproven. In deep squats, neither anterior nor posterior shear forces may be expected to reach magnitudes, which can harm an intact anterior or posterior cruciate ligament (28,87). Training studies with a duration of 8–21 weeks confirm that parallel (71) and deep back squats (18,77) do not have any negative effects on knee ligament stability. Measurements of knee stability followed immediately by the execution of parallel back squats with 1.6 times bodyweight demonstrate no acute changes (91). Instead cross-sectional studies with 27 powerlifters and 28 weightlifters confirm significantly ($p \leq 0.005$) higher knee stability in comparison with controls with low strength training experience (18). Chandler et al. (18) declared in a final comment: "The full squat may therefore be considered safe in terms of not causing permanent stretching of the knee ligaments" (p. 302). Compared with the quarter squat, the deeper joint positions of deep and parallel squats offer, despite lower training loads, better tension stimuli of the leg extensors for the development of muscle CSA (79), dynamic maximal strength, and dynamic speed-strength ability. This can be achieved with comparatively lower axial compressive and shear forces of the spinal column. According to the presented facts, the necessity of quarter squat training has to be seriously questioned.

Acknowledgments

These research projects were granted by Federal Institute of Sports Sciences, Germany. Reference numbers: AZ 070509/2007 and AZ 070510/2008.

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