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JOINT-ANGLE SPECIFIC STRENGTH ADAPTATIONS INFLUENCE IMPROVEMENTS IN POWER IN HIGHLY TRAINED ATHLETES

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ABSTRACT
Purpose. The purpose of this study was to examine the influence of training at different ranges of motion during the squat exercise on joint-angle specific strength adaptations. **Methods.** Twenty eight men were randomly assigned to one of three training groups, differing only in the depth of squats (quarter squat, half squat, and full squat) performed in 16-week training intervention. Strength measures were conducted in the back squat pre-, mid-, and post-training at all three depths. Vertical jump and 40-yard sprint time were also measured. **Results.** Individuals in the quarter and full squat training groups improved significantly more at the specific depth at which they trained when compared to the other two groups ($p < 0.05$). Jump height and sprint speed improved in all groups ($p < 0.05$); however, the quarter squat had the greatest transfer to both outcomes. **Conclusions.** Consistently including quarter squats in workouts aimed at maximizing speed and jumping power can result in greater improvements.

Key words: vertical jump, speed, squat depth, performance enhancement, sports conditioning

Introduction

The ultimate goal of a sports conditioning program is to enhance each individual athlete's athletic potential through a structured program of physical development and injury prevention [1]. To this end, specificity of training is a concept that should be of great importance to sports conditioning professionals. The body will adapt in very specific ways to meet the demands of a specific, re-occurring stress [2]. Resistance training that mimics the movements and demands of a given sport may enhance performance in that sport through specific adaptations in neuromuscular performance.

Siff [2] detailed this concept in a more complex, neurophysiologic manner stating that "it is vital to remember that all exercise involves information processing in the central nervous and neuromuscular systems, so that all training should be regarded as a way in which the body's extremely complex computing systems are programmed and applied in the solution of all motor tasks". It is important to consider how the specific stress applied to an athlete's body in conditioning will effect or stimulate the neuromuscular system, as well as how conditioning can result in improved information processing and physiological performance in specific sport skills.

Accordingly, alterations in the range of motion for a given exercise may, theoretically, result in different adaptations. Squat depth has been a topic of much discussion in the field and literature [3–11] with primary focus centering on strength improvements at different training depths. More broadly, this debate is an issue of joint-angle specificity, which has been examined for comparable strength improvements [12–17]. The topic of joint-angle specificity was initially examined with isometric and isokinetic training, which was shown to increase strength at or near the angles trained, and at or near angular velocities trained, with little or no adaptation at other angles/velocities [17].

Three primary squat depths have been characterized and discussed in the literature [18], including partial/quarter squats (40–60 degree knee angle), parallel/half squats (70–100 degree knee angle), and deep/full squats (greater than 100 degree knee angle). Range of motion variation during the squat exercise influences various biomechanical factors that relate to specificity of movement pattern, and can affect the development of force, rate of force development, activation and synchroniza-

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tion of motor units, and dynamic joint stability. Therefore, the manner in which an exercise changes based on range of motion is an important concept to examine.

The purpose of this study was to examine the influence of training at different squat depths on joint-angle specific strength as well as transfer to several sports-related performance variables. Understanding the effects of training at different ranges of motion can help the strength and conditioning professional to apply the most effective training strategy and further the performance enhancement advantages of evidence-based training prescriptions.

Material and methods

Subjects

Male college athletes of all sports at various schools (Division I, II, III and Junior College) were invited to participate in this research. Inclusion criteria included: 1) minimum of 2 years of consistent year-round training, 2) a minimum parallel squat 1RM of at least 1.5 times body weight, and 3) no physical condition that would impair aggressive sports conditioning and high-intense resistance training. A total of 38 athletes volunteered to participate. Of those, 32 met the minimum strength requirement. Two subjects experiencing tendonitis in the knee were excluded prior to group assignment. Two subjects withdrew during the initial testing period, resulting in 28 total subjects entering the training portion of the study. The methods and procedures for this study were evaluated and approved by an Institutional Review Board for research with Human Subjects and all participants provided informed consent. The majority (n = 24) of the subjects were football players, with track (n = 1), basketball (n = 2), and wrestling (n = 1) completing the sport backgrounds. Random assignment resulted in 3 groups with similar anthropometric measures, strength, and training experience. Descriptive data are presented in Table 1.

Procedures

Trained staff familiar with proper testing procedures and data handling performed all testing. Those conducting the pre-, mid-, and post-tests were blinded to the group assignment of each subject to avoid any potential bias. Experienced coaches implemented and oversaw the training program to ensure proper execution, tempo, and adherence to the prescribed program.

Strength testing was performed in accordance with published guidelines of National Strength and Conditioning Association [19]. Subjects performed one repetition maximum (1RM) testing at each of the three squat depths (quarter, half, and full) in three separate sessions, randomized in order, with a minimum of 72 hours between testing sessions. All 1RM values were achieved within 3 attempts. In a fourth and final testing session designed to examine the reliability of the strength data, each subject repeated the 1RM testing procedures for each depth (Intraclass Correlation Coefficient ranging from 0.95–0.98). Non-significant differences ($p > 0.05$) were found between 1RM values on the different testing days at each specific depth tested; however, the highest 1RM for each depth was utilized for data analysis. Testing at week 8 was performed in a 7-day period with each depth randomly tested on a separate day a minimum of 48 hours apart. Post-intervention testing was performed according to the same protocols explained for the pre-testing.

Vertical jump testing was performed according to protocols previously published [19]. Immediately following the dynamic warm-up in the first two testing sessions, all subjects were tested for their vertical jump using the Vertec (Vertec Sports Imports, Hilliard, OH). Subjects were given 3 attempts with the maximum height recorded. Non-significant differences were found between the two testing sessions ($p > 0.05$) but the highest jump height was recorded for data analysis.

Sprint testing was performed according to protocols previously published [19]. Following the dynamic warm-up in the first two testing sessions, all subjects performed a 40-yard sprint test. Electronic timing for the sprint was conducted with a wireless timing system (Brower Timing Systems, Draper, Utah). Subjects were given 2 attempts in each session with the maximum speed recorded. Non-significant differences were found between the two testing sessions ($p > 0.05$) but the fastest speed was recorded for data analysis.

All aspects of the training program were identical for each group with the exception of squat depth and absolute load. Within subject strength differences at each depth, due to the biomechanical disadvantage with increased depth, resulted in greater absolute loads being used at quarter and half squat depths. However, relative loads were the same for each group. The program

Table 1. Baseline Descriptive Data

Group	Age (years)	Weight (kg)	Pre-Quarter 1RM (kg)	Pre-Half 1RM (kg)	Pre-Full 1RM (kg)	Pre-VJ (cm)	Pre-40 (sec)
QTR	21.4 (3.2)	86.5 (25.6)	167.67 (13.95)	151.51 (15.12)	129.54 (17.23)	75.92 (15.06)	4.68 (0.18)
HALF	20.7 (2.1)	95.7 (32.1)	162.12 (12.22)	146.72 (11.54)	125.50 (14.09)	77.03 (11.05)	4.73 (0.18)
FULL	21.3 (1.3)	92.1 (23.8)	164.09 (13.18)	151.82 (12.80)	125.91 (18.38)	73.91 (14,25)	4.76 (0.20)

1RM – 1 repetition maximum, VJ – vertical jump, 40 – 40 yard sprint followed a daily undulating periodization sequence with intensity progressing from 8RM, 6RM, 4RM, to 2RM then reverting back to 8RM. Training weight was estimated using 1RM prediction equations based on the 1RM measures at the specific depth of training group, with notations made for rep ranges in each workout that required adjustments to the predicted values.

A split training routine was implemented to enable greater monitoring and control of lower body exercises. Lower body exercises (squats, power cleans, lunges, reverse hamstring curls, and step ups) were performed on Monday and Thursday, and upper body exercises performed on Tuesday and Friday. Squats (65%) and power cleans (25%) made up 90% of the training volume for the lower body with the other exercises added for general athletic preparation but at low volumes in each session (1–3 sets) and were identical for all three groups. Exercise order was kept constant for all groups and subjects. Wednesday, Saturday, and Sunday were designated as rest days with no exercise prescribed or allowed.

Lower body workouts included 4–8 sets of squats, at the prescribed depth, followed by each of the other exercises. A linear periodization adjustment in volume was made throughout the training program (weeks 1–2: 8 sets; weeks 3–4: 6 sets; weeks 5–6: 4 sets; weeks 7–10: 8 sets; weeks 11–14: 6 sets; weeks 15–16: 4 sets). A three-minute rest was provided between each set. This resulted in total volume, relative intensity, and workout sessions that were equated across the 16-week training intervention for all groups.

Squat depth was taught and monitored via videotaping throughout the training program. The first group performed full squats (FULL) with range of motion determined by the top of the thigh crossing below parallel to the floor and knee angles exceeding 110 degrees of flexion. The half squat group (HALF) trained at depths characterized by the top of the thigh reaching parallel to the floor with knee angles approximately 85–95 degrees of flexion. The final group performed quarter squats (QTR) with range of motion involving a squat to approximately 55–65 degrees of knee flexion. During the initial sessions, and during all testing, a goniometer (Orthopedic Equipment Company, Bourbon, Indiana) was used to measure the appropriate depth. Safety bars were raised or lowered in the squat rack for each subject to provide a visual gauge of the depth required. The coach provided immediate feedback if a slight alteration in depth was needed within a set.

A minimum of 30 workouts (out of 32) was required to be included in the final data analysis. This ensured that all subjects included in the analysis had completed roughly the same amount of work throughout the program. All 28 subjects met this requirement.

Statistical analyses

Data were analyzed using PASW/SPSS Statistics 20.0 (SPSS Inc, Chicago, IL, USA). The normality of the data was checked and subsequently confirmed with the Shapiro–Wilk test. Dependent variables were evaluated with a repeated measures analysis of variance (ANOVA) on group (QTR; HALF; FULL) × time (Baseline; Mid; Post). When a significant F-value was achieved, pairwise comparisons were performed using the Bonferroni post hoc procedure. The level of significance was fixed at $p \leq 0.05$. Partial Eta squared statistics (η^2) were analyzed to determine the magnitude of an effect independent of sample size. Pre/Post effect sizes were calculated for each group and performance measure [20]. The coefficient of the transfer was then calculated from squat result gains to vertical jump and sprinting speed via a calculation reported by Zatsiorsky [21]:

Transfer = Result Gain in nontrained exercise/Result Gain in trained exercise

Result Gain = Gain in performance/Standard deviation of performance

The associations between different measures were assessed by Pearson product moment correlation at baseline time. Values are expressed as mean ± SD in the text, and as mean ± SE in the figures.

Results

Quarter squat – 1RM-test

A group × time interaction effect was noted for quarter squat test ($p = 0.002$; $\eta^2 = 0.545$; see Figure 1a). A main effect of the group was observed ($p < 0.001$; $\eta^2 = 0.652$), as well as a main effect of the time was noted ($p = 0.012$; $\eta^2 = 0.322$).

Half squat – 1RM-test

A group × time interaction effect was noted for half squat test ($p < 0.001$; $\eta^2 = 0.563$; see Figure 1b). However, there was no significant a main effect of the group was observed ($p > 0.05$; $\eta^2 = 0.002$). A main effect of the time was noted ($p < 0.001$; $\eta^2 = 0.930$).

Full squat – 1RM-test

A group × time interaction effect was noted for full squat test ($p < 0.001$; $\eta^2 = 0.647$; see Figure 1c). However, there was no significant a main effect of the group was observed ($p = 0.074$; $\eta^2 = 0.278$). A main effect of the time was noted ($p < 0.001$; $\eta^2 = 0.623$).

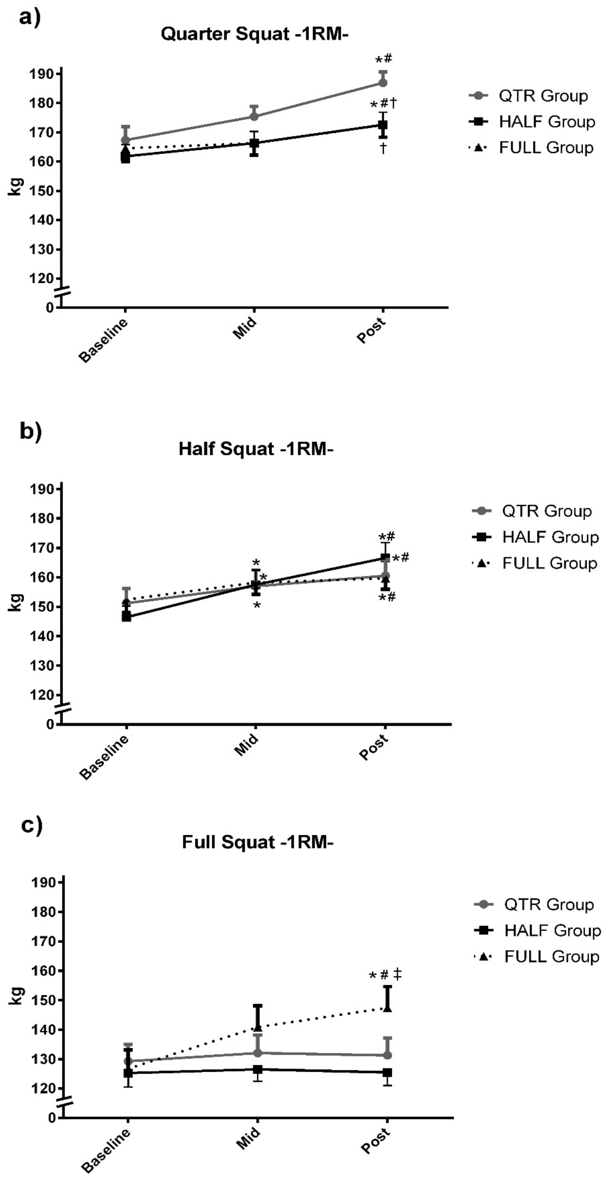
Vertical Jump Test

A group × time interaction effect was noted for vertical jump test ($p < 0.001$; $\eta^2 = 0.689$; see Figure 2). However, there was no significant a main effect of the group was observed ($p > 0.05$; $\eta^2 = 0.146$). A main effect of the time was noted ($p < 0.001$; $\eta^2 = 0.795$).

Sprint Test

A group × time interaction effect was noted for vertical jump test ($p < 0.001$; $\eta^2 = 0.615$; see Figure 3). However, no significant main effect of the group was observed ($p > 0.05$; $\eta^2 = 0.232$). A main effect of the time was noted ($p < 0.001$; $\eta^2 = 0.836$).

Percent change (Table 2) and effect size calculations (Table 3) demonstrated the greatest changes in strength at the specific depth at which each group trained. QTR squat improved 12% in the quarter squat 1RM, HALF 14% at half 1RM, and FULL improved 17% in the full squat 1RM. For VJ and 40-sprint, the QTR squat group showed the greatest treatment effect (VJ: 0.75; Sprin: –0.58), followed by HALF (VJ: 0.48; Sprint: –0.35), with FULL showing the lowest magnitude of training effect (VJ: 0.07; Sprint: –0.10). Transfer calculations (Table 4) somewhat mimicked the other trends in the data with QTR showing the greatest transfer to VJ (0.53), with HALF next (0.28), and FULL showing the least amount of transfer (0.06). For sprinting speed, QTR showed the greatest transfe (–0.41) with HALF second (–0.20) and FUL (–0.09) again showing the least transfer. Finally, correlation analysis (Table 5) demonstrated stronger relationships between the QTR squat group and both VJ ($r = 0.64$) and Sprint ($r = –0.74$) performances followed by HALF (r = 0.43 and $r = –0.57$) and FULL ($r = 0.31$ and $r = –0.49$).

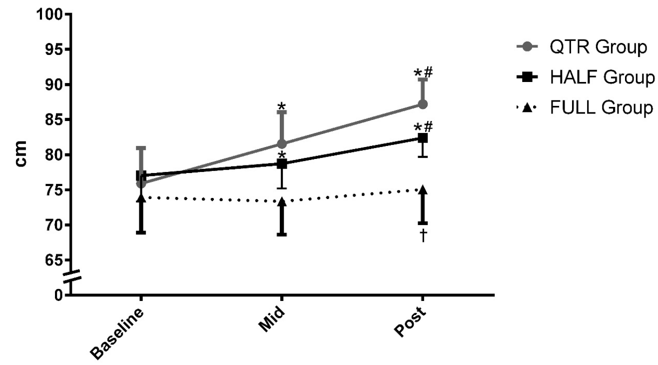


* significantly different from Baseline ($p < 0.05$)
\# significantly different from Mid (week 8) ($p < 0.05$)
† significantly different compared with the QTR group ($p < 0.05$)
‡ significantly different compared with the HALF group ($p < 0.05$)

Figure 1. Squat tests. Values are mean ± SE (QTR Group, $n = 9$; HALF Group, $n = 9$; FULL Group, $n = 10$)

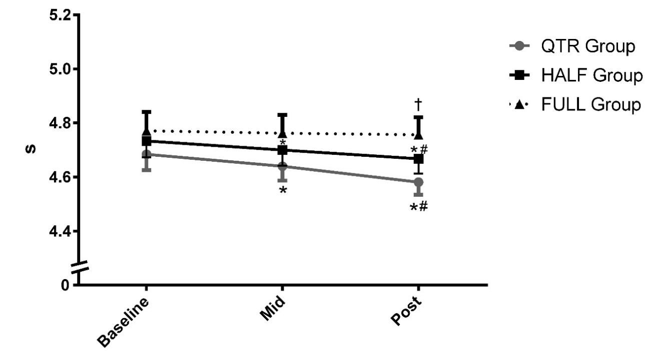
Discussion

Taken collectively, these findings support the use of shortened ranges of motion during squat training for improvements in sprint and jump performance among highly trained college athletes. This conclusion should stimulate further consideration among strength and con-



* significantly different from Baseline ($p < 0.05$)
\# significantly different from Mid (week 8) ($p < 0.05$)
† significantly different compared with the QTR group ($p < 0.05$)

Figure 2. Vertical Jump Test. Values are mean ± SE (QTR Group, $n = 9$; HALF Group, $n = 9$; FULL Group, $n = 10$)



* significantly different from Baseline ($p < 0.05$)
\# significantly different from Mid (week 8) ($p < 0.05$)
† significantly different compared with the QTR group ($p < 0.05$)

Figure 3. Sprint test. Values are mean ± SE (QTR Group, $n = 9$; HALF Group, $n = 9$; FULL Group, $n = 10$)

Table 2. Percet changes in performane measures

Group	Quarter Squat	Half Squat	Full Squat	VJ	40 sprint
QTR	0.12	0.06	0.02	0.15	–0.02
HALF	0.07	0.14	0.00	0.07	–0.01
FULL	0.00	0.05	0.17	0.01	0.00

VJ – vertical jump; 40 – 40 yard sprint

Table 3. Effect size calculations based on squat depth

Group	Quarter 1RM	Half 1RM	Full 1RM	VJ	40 sprint
QTR	1.41	0.62	0.12	0.75	–0.58
HALF	0.88	1.76	0.02	0.48	–0.35
FULL	0.05	0.59	1.14	0.07	–0.10

ES – (post-pre)/pre-test SD

Table 4. Coefficient of transfer calculations

Group	Quarter 1RM	Half 1RM	Full 1RM	VJ	40 sprint
QTR	1.00	0.44	0.08	0.53	–0.41
HALF	0.51	1.00	0.01	0.28	–0.20
FULL	0.05	0.52	1.00	0.06	–0.09

coefficient of transfer – result gain in nontrained exercise/result gain in trained exercise

Table 5. Bivariate correlations between strength capacities at different squat depths, vertical jump height, and sprint speed (n = 28)

Group	Quarter 1RM	Half 1RM	Full 1RM	VJ	40 sprint
Quarter 1RM	1	0.847**	0.722**	0.640**	–0.740**
Half 1RM	0.847**	1	0.693**	0.428*	–0.567**
Full 1RM	0.722**	0.693**	1	0.309	–0.490**
VJ	–0.640**	0.428*	0.309	1	–0.779**
Sprint	0.740**	–0.567**	–0.490**	–0.779**	1

** correlation is significant at the 0.01 (2-tailed)

ditioning coaches regarding the use of quarter squats in a sports conditioning program. Further examination of the risks, benefits, and implementation of squats of various depths is warranted, and will be discussed here.

Weiss et al. [7] conducted a study examining deep and shallow squat (corresponding to half and quarter squats in our study) and leg press training on vertical jump among untrained college students. Their study failed to find any significant changes in vertical jump for either group regardless of squat depth but two transfer calculations suggested greater transfer from the half squat training program to vertical jump. They did find statistically significant improvements in 1RM squat at the angle of training. The half squat group also improved 1RM at the quarter squat depth; however, the quarter squat training group did not improve 1RM performance in the half squat test. Our findings concur with the joint-angle specific improvement in strength relative to the angle where training occurred but differ in that our study did not show an improvement in quarter squats in the half or full squat training groups. Additionally, we found far less transfer from deep squat training to vertical jump. Several distinct differences exist between these two studies, perhaps accounting for the different findings. Our study utilized very highly trained athletes training with free weights instead of untrained college students who trained with machines. Our study was also nearly twice the length (16 weeks compared to 9 weeks). It is notable that in our study, the mid-test data (8 weeks) showed no significant findings, highlighting the need for longer studies to examine these important training issues more critically. It is also possible that as an individual becomes more highly trained, joint-angle specific adaptations are more pronounced and detectable.

Joint-angle specificity has been suggested to relate to neurological control [17]. Thepaut-Mathieu et al. [14] found increases in EMG activity at trained joint angles compared to untrained joint angles suggesting an increase in neural drive at the specific angles trained. Those data highlight the complexity of the nervous system processes for gathering information and responding to motor challenges. It appears that the nervous system gathers information relative to joint angles, contraction type, and angular velocities during training, responding with adaptations specific to those training demands.

An examination of the differences in squat 1RM at the three different depths in the current study provides valuable information relative to joint-angle specific loads and may assist in the development of an explanation of why quarter squats transfer more to jumping and sprinting speed. First, the quarter squat range of motion matches more closely the hip and knee flexion ranges observed in jumping and sprinting. That said, on average, athletes were able to squat 30–45% more in a quarter squat compared to the full squat depth (10–20% more when compared to half squat depth). Using 1RM testing at full squat depths to calculate and apply training loads through a full squat range of motion, results in training loads at the top of the range of motion representing less than 70% of maximum lifting capacity in that range of motion. Consistently training at 60–80% of maximum capacity may promote strength gains in less trained populations but would not be considered sufficient for optimal strength development among more highly trained populations [22]. Quarter squats would not be expected to improve full squat strength due to the lack of stress applied in full squat joint angles and the data in the current study supports that assertion. But the load during full squats appears to be insufficient to promote significant gains in strength in the quarter squat joint angles in highly trained populations. Thus, the loads that are calculated for training are specific to the joint angles at, or near, the angle at which testing occurs. They do not represent optimal training loads for all angles in the range of motion.

Isometric research [15] has shown that strength improvements only occur at or near the joint-angles where training occurs. Our data support this concept, as all of our groups were similar in gains at the half squat depth; however, significant differences were found at quarter and deep squats based on the training depths. The concept of joint-angle specificity as it relates to resistance training has generally been described as improvements in function at the joint-angles where training occurs. Under this philosophy, conventional thought has suggested that athletes must train through a full range of motion to ensure adaptations at all joint-angles. Given the data of the current study, it seems that strength improvements are specific to joint-angles that are sufficiently *overloaded*, not just joint-angles where training occurs. Therefore, we propose a change in perspective, based on the current data and theory, to reflect the concept of joint-angle *overload*.

It is suggested that improvements in muscular fitness will occur at the joint-angles that are sufficiently overloaded by the load placed upon them. In the conventional approach to measuring 1RM values at either a parallel or deep squat depth, and then performing squats at a certain percentage of that 1RM through a parallel or deep squat range of motion, the joint-angles involved in jumping and sprinting may not be sufficiently overloaded for maximal gains. Returning to the concepts proposed by Siff [2] regarding information processing during training, it is suggested that the neuromuscular system perceives, and adapts to, stresses applied during quarter squats much differently than full squats.

It is also important that the strength and conditioning professional differentiate between *transfer* and *value*. If the goal of a specific workout were to enhance sprinting or jumping, quarter squats would be the most effective range of motion based on the current data. But other squat depths may have value in preparing the athlete for competition, and coaches should examine the benefits, and risks, associated with squats of varying depths. If or when value exists, regardless of the amount of transfer directly to a given sports skill, an exercise or range of motion should be used to ensure that the athlete gains the full value of that exercise.

Different EMG activation patterns have been shown with various squat depths [10] and may provide evidence of specific value outside of transfer to sport skills. Full squats were shown to result in greater gluteus maximus activation with decreased hamstring involvement. Thus, squat depth may preferentially target recruitment of different muscle groups. Understanding the exact benefits or drawbacks of different exercises and ranges of motion is imperative to optimal training and strength and conditioning professionals should place high value on educating themselves and their clients regarding the pros and cons of a certain exercise or range of motion.

An additional consideration when selecting squat variations is the different stresses that each variation presents to the athlete. Schoenfeld [18] provides a detailed review of the various stresses that occur at the ankle, knee, and hip joints during the squat exercise at various depths. With changing loads and ranges of motion, stress appears to vary substantially. The increased load in a quarter squat, combined with the increased anterior shear force in that range, could present added risk of overuse injury if athletes only performed quarter squats. The same could be said of all squat depths and the best approach for health and performance enhancement may be to include different squat variations (i.e. back, front, split) at all three squat depths. Squats of different depths may need to be considered as separate exercises, or tools, employed for various purposes or to target specific muscles. A mixture of different squat depths, much like the use of various different exercises throughout a training program, may be the optimal approach to developing the total athlete. However, based on the data from this study, it is clear that the use of quarter squats is not only helpful, but also necessary for promoting maximal sprinting and jumping capabilities.

Conclusions

In summary given the significantly greater transfer to improvements in sprinting and jumping ability, the use of quarter squats during sports conditioning is recommended. Including quarter squats in workouts aimed at maximizing speed and jumping power can result in greater improvements in sport skills. While squats through a full range of motion may be useful in a general sports conditioning regimen, strength and conditioning professionals should consider the integration of quarter squats for maximizing sprinting and jumping ability.

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