McCormick JB, Drusch AS, Lynch DJ, et al. The Effect of Volitional Preemptive Abdominal Contraction on Biomechanical Measures During A Front Versus Back Loaded Barbell Squat. *IJSPT*. 2023;18(4):831-844. doi:10.26603/001c.84306

Original Research

The Effect of Volitional Preemptive Abdominal Contraction on Biomechanical Measures During A Front Versus Back Loaded Barbell Squat

Joseph B. McCormick[1,2a], Alexander S. Drusch[2], Darragh J. Lynch[2,3,4], Gesine H. Seeber[2,5,6], Katherine F. Wilford[2,7], Troy L. Hooper[2], Brad S. Allen[2], Dennis G. O'Connell[1], Maria J. Mena-Iturriaga[2,8], Kinyata J. Cooper[2], Phillip S. Sizer[2]

[1] Physical Therapy Department , Hardin–Simmons University, [2] Center for Rehabilitation Research, School of Health Professions, Texas Tech University Health Sciences Center, [3] Nvision Biomedical Technologies, [4] Southern California PT Fellowship Program, Kaiser Permanente, [5] University Hospital for Orthopaedics and Trauma Surgery Pius-Hospital, University of Oldenburg, [6] Department of Orthopedics, University of Groningen, University Medical Center Groningen, [7] Physical Therapy Department , Mary Baldwin University , [8] Facultad de Medicina Clínica Alemana , Universidad del Desarrollo

Keywords: biomechanics, abdominal bracing, electromyography, spine, squat

https://doi.org/10.26603/001c.84306

International Journal of Sports Physical Therapy

Vol. 18, Issue 4, 2023

Background

Weightlifting is growing in popularity among recreational and competitive athletes. The barbell back squat (BackS) is commonly included in these training programs, while the barbell front squat (FrontS) is commonly performed as a component of other lifts such as the power clean or clean and jerk, it is less commonly practiced in isolation.

Hypothesis/Purpose

The purpose of this study was to examine the effects of VPAC performance on trunk muscle and LE biomechanical responses during loaded BackS versus FrontS in healthy subjects.

Study Design

Controlled Laboratory Study

Methods

Healthy male subjects with the ability to perform a sub-maximal loaded barbell squat lift were recruited. Subjects completed informed consent, demographic/medical history questionnaires and an instructional video. Subjects practiced VPAC and received feedback. Surface electromyography (sEMG) electrodes and kinematic markers were applied. Muscles included were the internal oblique (IO), external oblique (EO), rectus abdominis, iliocostalis lumborum (ICL), superficial multifidi, rectus femoris, vastus lateralis, biceps femoris, and gluteus maximus. Maximal voluntary isometric contractions established reference sEMG values. A squat one-rep-max (1RM) was predicted by researchers using a three to five repetition maximum (3RM, 5RM) load protocol. Subjects performed BackS trials at 75% 1RM while FrontS trials were performed at 75% BackS weight, both with and without VPAC. Subjects performed three repetitions of each condition with feet positioned on two adjacent force plates. Significant interactions and main effects were tested using a 2(VPAC strategy) x 2(squat variation) and 2(VPAC strategy) x 2(direction) within-subject repeated measures ANOVAs. Tukey's Post-Hoc tests identified the location of significant differences.

---

[a] Corresponding author:
Joseph McCormick, PT, ScD
Physical Therapy Department, Hardin-Simmons University, Abilene, TX, USA
Fax: 325-670-5868
Phone: 325-670-1927
Email: joe.mccormick@hsutx.edu

Results

Trunk muscle activity was significantly higher during FrontS versus BackS regardless of VPAC condition. (IO: p=0.018, EO: p<0.001, ICL: p<0.001) VPAC increased performance time for both squat variations (p=.0011), which may be associated with decreased detrimental force potential on the lumbar spine and knees. VPAC led to improved ability to maintain a neutral lumbar spine during both squat variations. This finding is associated with decreased detrimental force potential on the lumbar spine.

Conclusions

Findings could help guide practitioners and coaches to choose squat variations and incorporate VPAC strategies during their treatments and/or training programs.

Level of Evidence

Level 3

INTRODUCTION

The popularity of weightlifting among recreational and competitive athletes is growing. The barbell back squat (BackS) is commonly included in training programs for these athletes. The BackS is defined as positioning a barbell across the shoulders, on the trapezius and slightly above the posterior deltoids, while allowing the hips and knees to flex until the thighs are parallel to the floor. The maneuver is completed by extending the hips and knees to return to a standing position.[1] The BackS is a common strengthening exercise for enhancing sports performance due to the movement's capacity to improve strength, induce muscle hypertrophy, and mimic common sport-related movements.[2,3]

The barbell front squat (FrontS) is less commonly performed in isolation for lower extremity (LE) strengthening and is considered comparable in overall muscle recruitment and performance.[1] The FrontS is defined by "positioning the barbell across the anterior deltoids and clavicles and fully flexing the elbows to position the upper arms parallel to the floor."[1] The maneuver is completed in a similar fashion the BackS. Though both squat variations demonstrate the ability to provide strength improvements, it is unknown which variation best optimizes training while minimizing injury risk.

Injury incidence among weightlifters is between 1.0-4.4 injuries/1,000 training hours.[4] Powerlifting movements such as BackS and deadlifts are commonly associated with self-reported low back injuries in recreational weightlifters.[5] Snug[6] reported low back pain sufferers demonstrated increased hip flexion and lumbar extension when squatting compared to normal subjects. The FrontS induces less forward trunk lean, which has been associated with decreased likelihood of lumbar injury.[7] The BackS, however, has been associated with increased forward trunk lean, potentially increasing lumbar spine shear forces. Similarly, detrimental LE forces are noted during the BackS versus the FrontS. Gullet et al[1] reported higher knee shear and compressive forces during the BackS compared to the FrontS.

Many investigators have examined neuromuscular control responses during both the BackS and FrontS. Various authors reported minimal erector spinae (ES) activation differences between the two squat variations.[1,2] Comfort et al,[8] however, reported the FrontS resulted in higher ES activation compared to the BackS. Based on their findings, these authors suggest the FrontS produces greater spinal stabilizer activation versus the BackS.[8]

Spinal stabilization occurs through muscle activation and a concurrent intra-abdominal pressure increase.[9] Volitional pre-emptive abdominal contraction (VPAC) has been used to stabilize the trunk during dynamic activities. For example, when VPAC is performed during a lifting task, it increases trunk and hip extensor force, internal oblique muscle thickness, and intra-abdominal pressure.[9,10] These events are associated with increased power during hip and trunk extension movements.[11] In addition, VPAC may reduce low back pain recurrence.[12] Research suggests VPAC produces spinal stabilization and a decreased ability to produce a VPAC may place individuals at higher injury risk.[13,14]

Two commonly described VPAC strategies are the abdominal drawing-in maneuver (ADIM) and the abdominal bracing maneuver (ABM). The ADIM involves volitional transversus abdominis contraction, whereas the ABM involves concurrent muscle contraction around the entire trunk. Where ADIM is effective in activating the transversus abdominus, ABM is more effective than ADIM in activating the transverse abdominus as well as the superficial multifidi and the internal oblique.[15-17] Maeo et al[18] reported that the ABM is commonly used in the health and fitness industry and is very effective in providing spinal stability. The ABM is more effective than the ADIM for reducing lumbar displacement and increasing trunk stability during external perturbations.[19]

No study has examined the impact of VPAC on different squat variations regarding trunk and LE kinetics, kinematics, and muscle activation. The purpose of this study was to examine the effects of VPAC performance on trunk muscle and LE biomechanical responses during loaded BackS versus FrontS in healthy subjects. The first hypothesis was that performing VPAC during BackS and FrontS trials would result in higher trunk muscle activation, regardless of squat variation. Next, the authors hypothesized the addition of VPAC will produce a significant change in LE muscle activation during a BackS and FrontS. For our third hypothesis, the authors speculated VPAC performance will result in significant differences in trunk and LE kinetics and kinematics. The fourth hypothesis surmised there would be significant differences in trunk and LE kinetics, kinematics, and muscle activity between the BackS and FrontS when performed without VPAC. For the fifth and final hypothesis, we postulated there would be significant differences in trunk and LE kinetics, kinematics, and muscle activity between the BackS and FrontS ascending and descending phases.

MATERIALS AND METHODS

This within-subject investigation examined the effect of VPAC on trunk and LE kinetics, kinematics, and muscle activation during two squat variations. All study-related measures followed the Helsinki Declaration's ethical principles. In conformity, the study protocol was reviewed and approved by the local university's Institutional Review Board for the Protection of Human Subjects (L19-046) before study initiation. Prior to enrollment, eligible subjects were informed about potential study-related risks and benefits and signed an approved informed consent.

SAMPLE

Based on a moderate effect size ($f = 0.2$), a desired 80% power, and $\alpha = 0.05$, a convenience sample of 26 healthy male subjects (18-35 years old) was recruited from a university population.[20]

INCLUSION AND EXCLUSION CRITERIA

Eligible subjects had to be able to (1) perform a sub-maximal loaded barbell squat lift; (2) perform VPAC on command; and (3) follow English language instructions. Exclusion criteria were: (1) Existing active spinal, upper extremity or LE pain meriting healthcare attention based on clinical judgement; (2) Upper or lower quarter injury requiring healthcare attention within 12 months prior to testing; (3) Any underlying neuromuscular or joint disease; (4) Any diagnosed and presently active abdominal, respiratory, or gastrointestinal condition; (5) Any significant spinal condition (including but not limited to scoliosis, spina bifida, tumors, present fractures, rheumatologic disorders) requiring healthcare attention; (6) Any blood clotting disorder or anticoagulant therapy; (7) History of abdominal or spinal surgery; (8) Any skin allergy preventing the use of electrode pads; and (9) BMI > 30.

INSTRUMENTATION

Thirty-six reflective markers were used to obtain 3-D trunk and LE kinematic data using an 8-camera motion capture system recorded at 100 Hz (VICON Nexus 2.3, Denver, CO). Changes in marker position were used to quantify range of motion elicited at each joint/plane, peak angles, and associated time ranges. In-ground force plates (Bertec, Columbus, OH) collected 3-D vertical (vGRF) and horizontal (hGRF) ground reaction force data at 1000 Hz. A freestanding EMG system (Noraxon USA, Scottsdale, AZ; 2000 Hz) gathered EMG data from the following muscles: internal oblique (IO), external oblique (EO), rectus abdominis (RA), iliocostalis lumborum (ICL), superficial multifidi (SM), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), and gluteus maximus (GM). Surface EMG data were collected bilaterally using dual Ag/AgCl EMG electrodes positioned on the subject according to the recommendations of previous investigators.[21-26] The EMG impedance were $>10^9$ MΩ, with a common mode rejection ratio > -92 dB and baseline noise <1.2 µV root-mean-square. Manual isometric testing appropriate to each respective muscle was used for proper electrode placement confirmation.

PREPARATORY PROCEDURES

Upon arrival for testing, each subject completed a medical history questionnaire and an investigator measured subjects' height (m) and weight (kg) to verify individual enrollment eligibility. Following, subjects watched an instructional video explaining the study purpose, potential risks and benefits, and all experimental procedures. Next, an investigator took anthropometric measurements relevant to the study. Next, subjects were instructed on performing the two squat variations. They were allowed to practice each squat with a 45-pound bar and received feedback. Following squat familiarization, subjects were instructed on how to perform VPAC. For the No-VPAC condition, subjects were taught to maintain a relaxed state. For the Yes-VPAC condition, subjects were cued to "gently inhale, then exhale, now stiffen your trunk as though you will be hit in the belly. Hold this contraction".[27] The tester palpated for proper and consistent abdominal contraction and visually confirmed absence of Valsalva maneuver and aberrant movement of the ribcage, shoulders, or pelvis.

Maximal voluntary isometric contraction (MVIC) was performed to normalize EMG signal amplitudes and allow measurement comparison among different muscles and between subjects.[28] For the RA, ICL, and dominant side EO and IO, subjects sat in a stable chair with the with arms crossed in front of their body and hips and knees flexed to 70° and 90°, respectively. Two straps were positioned at chest-level and around the subject's waist. The investigator stood behind the subject and instructed them to take in a breath and blow out while performing a maximal isometric axial spine rotation, while the investigator applied manual resistance to upper trunk. The knee extensors were tested in the seated position with the knee flexed to 90^o and the lower leg stabilized by an adjustable strap located at the subject's ankle and fixed to the base of the stable chair.

Hip extensor and knee flexor MVICs were performed with the subject positioned prone. For the hip extensors, the knees were flexed to 90^o. An adjustable strap was secured around the iliac crests and buckled around the table while a second adjustable strap was secured on the distal posterior thigh. The same procedure was followed for the knee flexors at 45^o of knee flexion and the strap secured around the ankle. For trunk and LE muscle normalization, subjects were asked to perform three consecutive 5-second trials of maximum contraction for each respective muscle The average was taken from the three trials for further analysis. Each MVIC was separated by a 1- to 2-minute rest period.

Following, subjects performed a five-minute warmup on a cycle ergometer. Then, they performed a squat according to the subject's own technique to a self-selected depth, where the thighs were near parallel to the ground. They repeated this procedure for two sets of five repetitions with 15 seconds of rest between sets. No attempt was made to control for speed, as that may have altered the lifting technique. Subjects were then allowed to stretch according to their prior lifting experience.[29]

Next, a researcher tested the subjects for their BackS predicted one repetition maximum (1RM) load using a three to five repetition maximum (3RM, 5RM) load protocol. This method uses submaximal loads that better represent those managed during routine training sessions.[30] Each subject was allowed two trials of the 3RM or 5RM in an attempt to establish their predicted 1RM. The weight of the first attempt was the subject's preference. Weight could be increased by a minimum of 5lb in subsequent trials. The subject performed repetitions to fatigue with a target of three to five repetitions achieved. Spotters stood on both ends of the bar to assist in unloading the weight as needed. Additionally, the spotters ensured that proper form was achieved during all repetitions. During all testing, subjects squatted with feet hip-width apart to a depth that achieved thighs parallel to the floor.[29,31,32] The squat depth was not strictly controlled so as to not alter the natural kinematics. A standardized rest period of two minutes was allowed after each attempt for adequate recovery.[29,32] The 1RM was predicted utilizing either the Epley equation (3RM equation) or the Brzycki equation (5RM equation) depending on each subject's performance.[30] The following formulae describe the prediction from 3RM or 5RM, accordingly:

> 3RM prediction equation: 1RM = [0.033 (reps)](rep wt) + rep wt
> 5RM prediction equation: 1RM = rep wt / [102.78 – 2.78(reps)]

Finally, researchers equipped subjects with retroreflective markers. A four-marker plate (i.e., quadrate marker) was placed at T10 and 36 kinematic markers were placed bilaterally at the following sites; iliac crest, ASIS, PSIS, upper and lower posterior thigh, lower anterior thigh, lateral and medial epicondyles of the knee, head of fibula, tibial tuberosity, lateral and medial malleoli of the ankle, the heel, head of the first, second and fifth metatarsals as established by previous investigators.[33,34] Subjects wore comfortable clothing during data collection and standardized lab shoes.

DATA COLLECTION

The squat rack was assembled over the force plates. Subjects were positioned with a foot on each force plate during the squat procedure. Subjects performed three loaded squats under each condition (BackS with VPAC, BackS without VPAC, FrontS with VPAC, FrontS without VPAC). The BackS was performed at a load level of 75% of the predicted 1RM (75%1RM).[2] Based on subjects' established capability during instrument testing, the FrontS was performed at a more conservative load level of 75% of the BackS 75%1RM. Though no established protocol exists in the literature to establish FrontS load based on a 1RM BackS calculation, this conservative load was chosen to ensure the safety of all subjects as well as to not fatigue subjects by performing two separate 1RM tests on the testing day. Squats were performed according to the same position and depth requirements as in 3-5RM predictive testing. All conditions were randomized for each subject to decrease the influence of fatigue and learning effect. A standardized rest period of 1-3 minutes (depending on subject preference) was allotted between trials to allow full recovery.[29,32]

STATISTICAL ANALYSIS

Reflective markers were tracked, labeled, and reconstructed using the Vicon Nexus software. Force and position data were filtered using a 4th order Butterworth digital filter (10 Hz cutoff frequency). These data were exported to MatLab (Version 9.5, R2018b, Mathworks, Inc, USA) for further processing using custom algorithms. A six-degrees-of-freedom link segment model was applied to the marker position data. A static standing calibration trial was used to define trunk and LE segmental coordinate systems and to calculate joint axes locations. Joint kinematics were calculated using an Xy'z'' Euler rotation sequence in an order of flexion/extension, abduction/adduction, and internal/external rotation. Trunk and pelvis segment kinematics were calculated as the orientation of the respective segment relative to the laboratory (global) coordinate system. Hip, knee, and ankle joint kinematics were calculated as the orientation of the distal segment relative to the proximal segment and mass location were estimated using previously published data.[35] The biomechanical dependent variables of interest were calculated from the processed time series data during the descent and ascent phase of the loaded squat lift.

Similarly, all EMG data were imported into a custom Matlab program. For every MVIC and submaximal MVIC trial raw EMG data was sampled at 1000 Hz, followed by a full-wave rectification and 4th order, 2-pass, no phase shift Butterworth filter with a 20-400 Hz bandpass. The EMG signals' average root mean square (RMS) for each MVIC and submaximal normalization trial was calculated for each muscle from the respective trial's final three-seconds of the contraction. Each five-second MVIC was trimmed to the desired three-second contraction followed by the RMS value calculation. Furthermore, each squat trial's raw EMG was sampled at 2000 Hz, followed by full-wave rectification and 4th order, 2-pass, no phase shift Butterworth filter with a 20-450 Hz bandpass. The RMS value was calculated for each squat repetition during the eccentric downward and concentric upward portions of the squat. All EMG data quality was checked based on power density spectrum observation and individual EMG graph inspection for artifacts and excessive noise prior to inclusion into the data set.

The trunk and LE muscle EMG data were reported as a percentage of the reference contraction values (or RMS-EMG%). Statistical analyses were conducted using the Statistical Package for Social Sciences for Windows.[36] Descriptive data analyses established values for central tendency (means) and dispersion (standard deviation and 95% confidence intervals [CI]). Data normality was established using the Shapiro Wilk test (p-value >.05), as well as skewness and kurtosis (between -2.0 and +2.0). Data sphericity was assessed using a Mauchly's test for Sphericity (p>.05).

A 2 (VPAC strategy) x 2(squat variation) as well as a 2 (squat variation) x 2 (direction - descend/ascend phase of each squat) within-subject, repeated measures ANOVA was used to test for interactions and significant main effects of: (1) VPAC on trunk muscle activity during BackS and FrontS; (2) VPAC on LE muscle activation during BackS and FrontS; (3) VPAC on trunk and LE kinetics and kinematics during BackS and FrontS; (4) BackS versus FrontS squat variations on trunk and LE kinetics, kinematics, and muscle activation; and (5) ascending and descending phases of both BackS and FrontS on trunk and LE kinetics, kinematics, and muscle activity, respectively. Post-hoc comparisons were used to locate significant differences. Bonferroni corrections to an alpha level of .05 were implemented in order to reduce the chance of a type 1 error.

RESULTS

Descriptive data were established for the 26 male subjects' age (22.8 ± 3.1 years), height (182.4. ±7.4 cm), weight (84.3 ± 11kg) and BMI (25.3 ±2.9kg/m^2). Moreover, descriptive data were established for subjects' 5RM BackS weight (240.4 ±44.0 lbs), predicted 1RM BackS weight (270.5 ±49.6 lbs), BackS working weight (202.8 ±37.2 lbs), and FrontS working weight (152.1 ±27.9 lbs).

Considering the first hypothesis, VPAC use did not result in significant trunk muscle activity changes as measured by surface EMG in either squat variation (Table 1). Regarding the second hypothesis, no significant main effect was observed for LE muscle activation based on VPAC condition or squat variation (Table 2).

Regarding the third hypothesis, the use of VPAC resulted in significant increased time to reach sagittal plane peak hip and knee angles for both squat variations (Table 3, Table 4). Furthermore, a significant main effect was observed for spinal position, where the addition of VPAC resulted in significantly decreased lumbar extension in both squat variations (Table 5). The addition of VPAC resulted in increased performance time during descent, ascent, and total time for both squat variations. While the descent of both squat variations demonstrated increased performance duration, the BackS demonstrated a longer decent performance time versus FrontS (Table 6).

Regarding the fourth hypothesis, there was a significant main effect for trunk muscle activity based on squat variation. FrontS resulted in significantly higher trunk muscle activity in the IO and EO muscles as well as the ICL (Table 1). At the same time, FrontS demonstrated less lumbar extension than BackS. Finally, a significant main effect was noted regarding moments at the right hip and ankle (Table 7). In the BackS, the moment was greater at both the hip and ankle joints in the sagittal plane.

Regarding the fifth hypothesis, a significant main effect for trunk muscle activity during the descending versus ascending phases of both squat variations was observed regardless of VPAC condition. Here, the IO and EO exhibited greater activity during the descending phase of both squat variations (Table 1).

DISCUSSION

The purpose of this study was to assess the effect of VPAC performance on trunk muscle and LE biomechanical responses during loaded BackS versus FrontS in healthy subjects. This study was the first to demonstrate VPAC performance resulted in slower movement performance time and a more neutral lumbar spine position during weighted barbell squats. In addition, this study supports the findings of previous researchers, showing that FrontS resulted in increased erector spinae muscle activity when compared to BackS, regardless of VPAC condition. Furthermore, this study is the first to our knowledge to demonstrate increased IO and EO muscle activation during FrontS versus BackS.

ADIM has been shown to be very useful for onset activation re-education at the beginning of rehabilitation but not as useful as ABM for more functional/highly demanding tasks. This is likely due to the fact that ABM creates a co-contraction of several trunk muscles providing spinal stability throughout the duration of functional/highly demanding activity.[37-39] Regarding the first hypothesis, there was no detectable change in abdominal muscle activity in response to different VPAC conditions. This lack of change is likely due to a ceiling effect secondary to the load placed on the tested muscles. At a load of 75% 1RM, it is possible trunk muscle bracing occurred automatically, regardless of VPAC condition. Additionally, subjects may not have been given sufficient time between VPAC instruction and trial completion for abdominal muscle deactivation during the no-VPAC condition. Subjects were instructed on VPAC activation shortly before performing the squat trials. It is possible the subjects were not able to suspend use of this new skill between trials. In addition, based on previous experience, subjects may be accustomed to bracing when performing loaded barbell squats and experienced a challenge when attempting to consciously not brace.

Similarly, there was no significant difference in LE muscle activity based on VPAC condition or squat variation. These findings are consistent with those of Gullet[1] in which they observed no significant difference in overall LE muscle activation between the FrontS and BackS. Though participants lifted less weight with the FrontS, the overall muscle activity was not significantly different between squat variations. Therefore, the same benefits from the workout may be achieved with the added benefit of decreasing potentially detrimental forces on the knees by performing FrontS rather than BackS.

Regarding the third hypothesis, VPAC resulted in decreased lumbar extension during both squat variations. Shoenfeld[40] proposed squatting with a flexed lumbar spine decreases erector spinae's ability to accommodate compressive loads and potentially increases injury risk. The authors

Table 1. Repeated measures ANOVA tests of Within-Subjects effects for trunk EMG

Analyses	Muscle	df	*F*	Sig	PES	PWR
Barbell●VPAC●LiftPhase	IO	1, 25	2.379	0.136	0.087	0.317
VPAC●LiftPhase	IO	1, 25	0.222	0.642	0.009	0.074
Barbell●LiftPhase	IO	1, 25	1.037	0.318	0.04	0.165
Barbell●VPAC	IO	1, 25	1.760	0.197	0.066	0.248
LiftPhase	IO	1, 25	6.910	**0.014***	0.217	0.715
VPAC	IO	1, 25	2.089	0.161	0.077	0.285
Barbell	IO	1, 25	6.444	**0.018***	0.205	0.684
Analyses	**Muscle**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	EO	1, 25	0.62	0.438	0.024	0.118
VPAC●LiftPhase	EO	1, 25	0.001	0.974	< .001	0.05
Barbell●LiftPhase	EO	1, 25	1.507	0.231	0.057	0.219
Barbell●VPAC	EO	1, 25	0.091	0.765	0.004	0.06
LiftPhase	EO	1, 25	6.2	**0.02***	0.199	0.668
VPAC	EO	1, 25	1.594	0.218	0.06	0.229
Barbell	EO	1, 25	30.562	< **.001***	0.55	1
Analyses	**Muscle**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	ICL	1, 25	0.509	0.482	0.392	0.105
VPAC●LiftPhase	ICL	1, 25	0.13	0.722	< .001	0.064
Barbell●LiftPhase	ICL	1, 25	3.705	0.066	0.038	0.457
Barbell●VPAC	ICL	1, 25	0.138	0.713	0.005	0.065
LiftPhase	ICL	1, 25	0.976	0.333	0.129	0.158
VPAC	ICL	1, 25	0.007	0.933	0.005	0.051
Barbell	ICL	1, 25	16.134	**< .001***	0.20	0.971
Analyses	**Muscle**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	MF	1, 25	0.246	0.624	0.01	0.076
VPAC●LiftPhase	MF	1, 25	0.076	0.785	0.003	0.058
Barbell●LiftPhase	MF	1, 25	1.315	0.262	0.05	0.197
Barbell●VPAC	MF	1, 25	0.219	0.644	0.009	0.073
LiftPhase	MF	1, 25	0.227	0.638	0.009	0.074
VPAC	MF	1, 25	0.387	0.54	0.015	0.092
Barbell	MF	1, 25	0.003	0.955	< .001	0.05

Barbell = front or back barbell position, VPAC = yes/AB or no/NB, LiftPhase = ascend or descend, Muscle: IO = internal oblique, EO = external oblique, RA = rectus abdominus, ICL = iliocostalis lumborum, MF = multifidi (all muscles refer to right side); df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to $\alpha = .025$ for EO, IO pairing and $\alpha = .025$ for Mf, IC pair); *significant result.

suggest the more neutral spine achieved during VPAC conditions may optimize trunk muscle alignment by placing subjects in a more mechanically advantageous position, especially during the FrontS. The FrontS inherently results in less lumbar extension, however, the addition of VPAC demonstrated a significant decrease in lumbar extension in both squat variations. When VPAC was incorporated, the spine was able to remain in a more "neutral" alignment, potentially resulting in decreased shear forces and rendering the lumbar spine at less injury risk.

Previous investigators have reported individuals must lean forward to maintain balance during squats, leading to increased hip flexion and moving the center of gravity further away from the lumbar spine.[1,7] This leads to increased torque at the lumbar spine, ultimately increasing shear force potential.[1,7] The forward lean can also result in a decreased tissue tolerance to compressive load as well as a load transfer from muscles to passive tissues such as the discs, increasing the likelihood of disc injury.[41] Future research should further investigate the impact of VPAC on trunk position and injury risk in light of these findings.

As observed in this study, VPAC performance decreased performance speed in both squat variations. This has the potential to benefit weightlifters with respect to reducing injury risk. Hattin et al[42] reported increased squat performance speed results in significantly higher tibiofemoral joint anteroposterior shear and compressive forces. In addition, a common finding with increased squatting speed is a

Table 2. One-way ANOVA tests of Within-Subjects effects for LE EMG

Analyses	Muscle	df	F	Sig	PES	PWR
Barbell●VPAC●LiftPhase	GM	1, 25	0.469	0.5	0.018	0.101
VPAC●LiftPhase	GM	1, 25	0.635	0.433	0.025	0.12
Barbell●LiftPhase	GM	1, 25	0.503	0.485	0.02	0.105
Barbell●VPAC	GM	1, 25	4.165	0.052	0.143	0.501
LiftPhase	GM	1, 25	3.251	0.083	0.115	0.411
VPAC	GM	1, 25	4.868	0.037	0.163	0.564
Barbell	GM	1, 25	0.001	0.974	< .001	0.05
Analyses	**Muscle**	**df**	**F**	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	BF	1, 25	5.108	0.033	0.17	0.584
VPAC●LiftPhase	BF	1, 25	0.77	0.389	0.03	0.135
Barbell●LiftPhase	BF	1, 25	4.35	0.047	0.148	0.518
Barbell●VPAC	BF	1, 25	0.41	0.528	0.016	0.095
LiftPhase	BF	1, 25	8.073	**0.009***	0.244	0.78
VPAC	BF	1, 25	0.193	0.664	0.008	0.071
Barbell	BF	1, 25	2.748	0.11	0.099	0.357
Analyses	**Muscle**	**df**	**F**	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	RF	1, 25	2.513	0.126	0.091	0.332
VPAC●LiftPhase	RF	1, 25	0.445	0.511	0.017	0.098
Barbell●LiftPhase	RF	1, 25	0.157	0.695	0.006	0.067
Barbell●VPAC	RF	1, 25	9.617	**0.005***	0.278	0.846
LiftPhase	RF	1, 25	0.008	0.928	< .001	0.051
VPAC	RF	1, 25	0.567	0.458	0.022	0.112
Barbell	RF	1, 25	0.214	0.648	0.008	0.073
Analyses	**Muscle**	**df**	**F**	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	VL	1, 25	0.238	0.63	0.009	0.076
VPAC●LiftPhase	VL	1, 25	1.097	0.305	0.042	0.172
Barbell●LiftPhase	VL	1, 25	0.574	0.456	0.022	0.113
Barbell●VPAC	VL	1, 25	0.059	0.811	0.002	0.056
LiftPhase	VL	1, 25	0.005	0.943	< .001	0.051
VPAC	VL	1, 25	1.038	0.318	0.04	0.165
Barbell	VL	1, 25	0.504	0.484	0.02	0.105

Barbell = front or back barbell position, VPAC = yes/AB or no/NB, LiftPhase = ascend or descend, Muscle: GM = gluteus maximus, BF = bicep femoris, RF = rectus femoris, VL = vastus lateralis (all muscles refer to right side); df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to α = .025 for GM, BF pairing and α = .025 for RF, VL pair); *significant result.

concurrent "bounce" at the bottom of the squat, potentially increasing these compressive forces up to 33%.[43] Lavender et al[44] found faster lifting speed resulted in a greater lumbar spine flexion moment. Similarly, Greenland et al[45] reported peak lumbar compressive forces occurred at higher speeds. The authors propose the act of attending to VPAC performance improved task vigilance and changed the central nervous system programming during the lifting task. Thus, future research should explore both lifting speed optimization and the effects of VPAC.

Though the authors did not see differences in trunk muscle activation related to VPAC, they did see a difference in trunk muscle activity based on squat variation. With reference to the fourth hypothesis, IO and EO muscles as well as the ICL demonstrated greater activity during the FrontS. The authors propose this is related to the more neutral lumbar spine alignment seen in the FrontS. Similarly, Comfort et al[8] found the FrontS demonstrated greater ES activity. However, Clark et al[2] and Gullet et al[1] found no difference in ES activity comparing FrontS to BackS.

The authors also noted a significant main effect regarding right hip and ankle joint moments in which both moments were greater in the BackS. This finding is expected due to barbell position inducing a forward trunk lean during the BackS versus the FrontS. The authors propose that in addition to reducing detrimental lumbar spine forces, use of the FrontS should be considered to also minimize hip and ankle forces. These findings are consistent with those

Table 3. One-way ANOVA tests of Within-Subjects effects for kinematic times in the sagittal plane

Analyses	Joint	df	*F*	Sig	PES	PWR
Barbell•VPAC	Lumbar Spine	1, 25	0	0.999	< .001	0.05
VPAC	Lumbar Spine	1, 25	4.787	0.038	0.161	0.557
Barbell	Lumbar Spine	1, 25	0.158	0.694	0.006	0.067
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Hip	1, 25	0.132	0.719	0.005	0.064
VPAC	Right Hip	1, 25	8.79	**0.007***	0.26	0.813
Barbell	Right Hip	1, 25	2.522	0.125	0.092	0.333
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Knee	1, 25	0.058	0.811	0.002	0.056
VPAC	Right Knee	1, 25	9.749	**0.004***	0.281	0.851
Barbell	Right Knee	1, 25	1.247	0.275	0.048	0.189
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Ankle	1, 25	0.101	0.753	0.004	0.061
VPAC	Right Ankle	1, 25	5.753	0.024	0.187	0.635
Barbell	Right Ankle	1, 25	1.744	0.199	0.065	0.246

Barbell = front or back barbell position, VPAC = yes/AB or no/NB; df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to α = .0125 for lumbar, R hip, R knee and R ankle); *significant result.

Table 4. One-way ANOVA tests of Within-Subjects effects for kinematic times in the frontal plane

Analyses	Joint	df	*F*	Sig	PES	PWR
Barbell•VPAC	Right Knee	1, 25	0.636	0.433	0.025	0.12
VPAC	Right Knee	1, 25	1.008	0.325	0.039	0.162
Barbell	Right Knee	1, 25	1.886	0.182	0.07	0.262
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Left Knee	1, 25	0.709	0.408	0.028	0.128
VPAC	Left Knee	1, 25	2.705	0.113	0.098	0.353
Barbell	Left Knee	1, 25	0.053	0.821	0.002	0.056

Barbell = front or back barbell position, VPAC = yes/AB or no/NB, Joint = left or right knee; df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to α = .025 for R knee, L knee pairing); *significant result.

of Gullet[1] in which they observed no significant difference in LE muscle activation between the FrontS and BackS. In addition, they also found less potentially detrimental forces on the knees during the FrontS. Future research should further explore these findings.

Regarding the final hypothesis, the authors noted a difference in trunk muscle activity during the descending versus ascending phases of both squat variations, regardless of VPAC condition. In this study the IO and EO muscles exhibited greater activity during the descending phase of both squat variations, with exception to FrontS without bracing. In addition, the authors did not see a difference in ES activity between descending versus ascending phases in either squat variation. This finding is not consistent with previous literature that found increased ES activity during the squat ascent.[1,7]

One major difference in the current study was the inclusion of IO and EO EMG measures, whereas previous studies focused on the ES. These findings point to the possibility that the oblique muscles play a valuable role in providing stability during the squat descent. The oblique muscles, when contracted bilaterally, flex the trunk and posteriorly tilt the pelvis. During a squat, this action is necessary to counteract the strong erector spinae activity that serves to extend the spine, creating a relative anterior tilt of the pelvis.[46] Haddas et al[47] found that VPAC increased EO activity during uniplanar drop landing and uniplanar symmetrical box lifting tasks. Additionally, they did not note a difference between descending or ascending phases in the box lift.

The authors propose the key difference in findings is due to the significantly greater load the current participants were under while performing both the FrontS and BackS. With a greater load, subjects must accommodate for the increased stress applied to their trunks. This is especially likely during the decent-to-ascent-transition where lifters may struggle to maintain a neutral posture. In this transition, lifters often lean further forward to maintain bal-

Table 5. One-way ANOVA tests of Within-Subjects effects for kinematic angles in the sagittal plane

Analyses	Joint	df	*F*	Sig	PES	PWR
Barbell●VPAC	Lumbar Spine	1, 25	0.007	0.935	< .001	0.051
VPAC	Lumbar Spine	1, 25	7.388	**0.012***	0.228	0.743
Barbell	Lumbar Spine	1, 25	0.172	0.682	0.007	0.068
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC	Right Hip	1, 25	3.683	0.066	0.128	0.454
VPAC	Right Hip	1, 25	1.12	0.3	0.043	0.175
Barbell	Right Hip	1, 25	8.366	**0.008***	0.251	0.794
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC	Right Knee	1, 25	4.406	0.046	0.15	0.523
VPAC	Right Knee	1, 25	0.102	0.752	0.004	0.061
Barbell	Right Knee	1, 25	51.555	< **.001***	< .001	1
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC	Right Ankle	1, 25	1.393	0.248	0.053	0.206
VPAC	Right Ankle	1, 25	4.554	0.043	0.154	0.537
Barbell	Right Ankle	1, 25	4.147	0.052	0.142	0.499

Barbell = front or back barbell position, VPAC = yes/AB or no/NB, Joint; df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to α = .0125 for lumbar, R hip, R knee and R ankle); *significant result.

ance, compensating with increased lumbar extension. As a result, the IO and EO may be elongated into a mechanically disadvantageous position and therefore demonstrate decreased EMG activity. As previously stated, slower performance of these movements decreases the likelihood of detrimental forces occurring at the lumbar spine and LE. Future studies should further investigate the oblique muscles' role in trunk stabilization during squatting activities and the influence of VPAC.

STUDY LIMITATIONS, DELIMITATIONS, AND FUTURE RESEARCH

The results of this study must be interpreted considering some limitations. As discussed above, it is likely our subjects experienced a ceiling effect with respect to trunk muscle activity during the squat lifting sequence. It is possible there was no significant muscle activity change in response to VPAC because the load subjects were under resulted in a trunk muscle contraction regardless of VPAC condition.

Another limitation centers on the brief time subjects were given for executing a new skill. Subjects were introduced to VPAC performance shortly before performing both squat variations. Though provided with clear instructions for VPAC performance and verified by an expert, it is possible the subjects had not mastered this skill prior to squat performance. Hall et al[48] reported one VPAC training session may not be sufficient to improve EO, IO, and ES muscle EMG outputs. In future studies, two separate robust practice sessions may be beneficial for enhancing VPAC performance.

This study presents with three delimitations. First, subjects included a male convivence sample, which is consistent with other investigators.[2,7,8] However, inclusion of females would improve generalizability of findings. Moreover, the use of a convenience sample risks having an overly homogenous sample, or one with significant variability, impeding true representation of the greater population. Future studies should attempt other sampling methods for improved results generalizability.

Secondly, weighted barbell squats were a fairly specialized movement involving a lifting activity at a predicted 75% of 1RM. Comfort et al[8] discussed the need for testing subjects at higher training loads to adequately represent the athletic population. However, such higher loads may not be representative of the weight level used by the general population. Future studies should examine similar parameters at multiple different weight levels, including higher levels associated with competitive athletes.

Finally, inferences cannot be drawn between these findings and other functional lifting activities, such as those found in the industrial setting. For example, most lifting tasks in industrial settings involve loads that are lifted and/or carried in front of the body. While, the barbell BackS has little application to industrial lifting tasks, the barbell FrontS exhibits potential applicability. To support generalizing to the industrial population, future research should examine the effects of VPAC on functional FrontS lifting activities, deadlifting, box lifting, and farmer's carry lifts that better represent industrial lifting.

CONCLUSION

The results of this study indicate that trunk muscle activity was higher during FrontS versus BackS regardless of VPAC condition. Regarding VPAC, this study demonstrated increased time of performance for both squat variations and improved ability to maintain a neutral lumbar spine. Both adaptations have been associated with decreased detrimen-

Table 6. One-way ANOVA tests of Within-Subjects effects for barbell time variables

Analyses	**Time**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC	Total Time	1, 25	0.756	0.393	0.029	0.133
VPAC	Total Time	1, 25	7.461	**0.011***	0.23	0.747
Barbell	Total Time	1, 25	3.867	0.06	0.134	0.472
Analyses	**Time**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	Up/Down	1, 25	2.939	0.099	0.105	0.378
VPAC●LiftPhase	Up/Down	1, 25	0.863	0.362	0.033	0.145
Barbell●LiftPhase	Up/Down	1, 25	6.505	**0.017***	0.206	0.689
Barbell●VPAC	Up/Down	1, 25	< .001	0.985	< .001	0.05
LiftPhase	Up/Down	1, 25	10.461	**0.003***	0.295	0.874
VPAC	Up/Down	1, 25	8.255	**0.008***	0.248	0.789
Barbell	Up/Down	1, 25	12.298	**0.002***	0.33	0.921
Analyses	**Time**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	Velocity	1, 25	0.721	0.404	0.028	0.129
VPAC●LiftPhase	Velocity	1, 25	0.014	0.905	0.001	0.052
Barbell●LiftPhase	Velocity	1, 25	1.148	0.294	0.044	0.178
Barbell●VPAC	Velocity	1, 25	0.106	0.748	0.004	0.061
LiftPhase	Velocity	1, 25	4.287	0.049	0.146	0.512
VPAC	Velocity	1, 25	1.497	0.233	0.056	0.218
Barbell	Velocity	1, 25	0.769	0.389	0.03	0.135
Analyses	**Time**	**df**	**F**	**Sig**	**PES**	**PWR**
Barbell●VPAC●LiftPhase	Acceleration	1, 25	1.065	0.312	0.041	0.168
VPAC●LiftPhase	Acceleration	1, 25	0.018	0.895	0.001	0.052
Barbell●LiftPhase	Acceleration	1, 25	1.527	0.228	0.058	0.221
Barbell●VPAC	Acceleration	1, 25	1.542	0.226	0.058	0.223
LiftPhase	Acceleration	1, 25	0.708	0.408	0.028	0.128
VPAC	Acceleration	1, 25	0.984	0.331	0.038	0.159
Barbell	Acceleration	1, 25	0.617	0.439	0.024	0.118

Barbell = front or back barbell position, VPAC = yes/AB or no/NB, LiftPhase = ascend or descend; time variables: time up, time down, total time, velocity up, acceleration; df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significant results at $\alpha = .05$ for total time and significance was familywise adjusted to $\alpha = .025$ for time down, time up pairing and velocity up, down pairing and acceleration up, down pairing); *significant result.

tal lumbar spine and knee forces. These findings can help guide clinicians and coaches to incorporate weighted FrontS and VPAC strategies into treatments and/or training programs.

CONFLICT OF INTEREST

Dr. Sizer is the co-founder of TKQuant LLC. This relationship/patent has nothing to do with this submitted work. All other authors declare no conflicts of interest.

Submitted: February 27, 2023 CDT, Accepted: June 16, 2023 CDT

Table 7. One-way ANOVA tests of Within-Subjects effects for sagittal plane joint moments

Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Hip	1, 25	0.361	0.554	0.014	0.089
VPAC	Right Hip	1, 25	0.078	0.782	0.003	0.058
Barbell	Right Hip	1, 25	86.734	**< .001***	0.776	1
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Knee	1, 25	0.23	0.636	0.009	0.075
VPAC	Right Knee	1, 25	3.27	0.083	0.116	0.413
Barbell	Right Knee	1, 25	2.231	0.148	0.082	0.301
Analyses	**Joint**	**df**	***F***	**Sig**	**PES**	**PWR**
Barbell•VPAC	Right Ankle	1, 25	1.058	0.314	0.041	0.167
VPAC	Right Ankle	1, 25	2.839	0.104	0.102	0.367
Barbell	Right Ankle	1, 25	76.201	**< .001***	0.753	1

Barbell = front or back barbell position, VPAC = yes/AB or no/NB; df = degrees of freedom, F = f-statistic, Sig = significance, PES = partial eta squared effect size, PWR = power. (significance was familywise adjusted to α = .0167 for R hip, R knee and R ankle); *significant result.

REFERENCES

1. Gullett JC, Tillman MD, Gutierrez GM, Chow JW. A biomechanical comparison of back and front squats in healthy trained individuals. *J Strength Cond Res*. 2009;23(1):284-292. doi:10.1519/jsc.0b013e31818546bb

2. Clark DR, Lambert MI, Hunter AM. Muscle activation in the loaded free barbell squat: a brief review. *J Strength Cond Res*. 2012;26(4):1169-1178. doi:10.1519/jsc.0b013e31822d533d

3. Escamilla RF. Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc*. 2001;33(1):127-141. doi:10.1097/00005768-200101000-00020

4. Aasa U, Svartholm I, Andersson F, Berglund L. Injuries among weightlifters and powerlifters: a systematic review. *Br J Sports Med*. 2017;51(4):211-219. doi:10.1136/bjsports-2016-096037

5. Weisenthal BM, Beck CA, Maloney MD, DeHaven KE, Giordano BD. Injury Rate and Patterns Among CrossFit Athletes. *Orthop J Sports Med*. 2014;2(4):2325967114531177. doi:10.1177/2325967114531177

6. Sung PS. A compensation of angular displacements of the hip joints and lumbosacral spine between subjects with and without idiopathic low back pain during squatting. *J Electromyogr Kinesiol*. 2013;23(3):741-745. doi:10.1016/j.jelekin.2013.02.003

7. Yavuz HU, Erdağ D, Amca AM, Aritan S. Kinematic and EMG activities during front and back squat variations in maximum loads. *J Sports Sci*. 2015;33(10):1058-1066. doi:10.1080/02640414.2014.984240

8. Comfort P, Pearson SJ, Mather D. An electromyographical comparison of trunk muscle activity during isometric trunk and dynamic strengthening exercises. *J Strength Cond Res*. 2011;25(1):149-154. doi:10.1519/jsc.0b013e3181fb412f

9. Behm DG, Drinkwater EJ, Willardson JM, Cowley PM, Canadian Society for Exercise Physiology. Canadian Society for Exercise Physiology position stand: The use of instability to train the core in athletic and nonathletic conditioning. *Appl Physiol Nutr Metab*. 2010;35(1):109-112. doi:10.1139/h09-128

10. Tayashiki K, Takai Y, Maeo S, Kanehisa H. Intra-abdominal Pressure and Trunk Muscular Activities during Abdominal Bracing and Hollowing. *Int J Sports Med*. 2016;37(2):134-143. doi:10.1055/s-0035-1559771

11. Tayashiki K, Maeo S, Usui S, Miyamoto N, Kanehisa H. Effect of abdominal bracing training on strength and power of trunk and lower limb muscles. *Eur J Appl Physiol*. 2016;116(9):1703-1713. doi:10.1007/s00421-016-3424-9

12. Aleksiev AR. Ten-year follow-up of strengthening versus flexibility exercises with or without abdominal bracing in recurrent low back pain. *Spine*. 2014;39(13):997-1003. doi:10.1097/brs.0000000000000338

13. Mcgill S. Core Training: Evidence Translating to Better Performance and Injury Prevention. *Strength Cond J*. 2010;32(3):33-46. doi:10.1519/ssc.0b013e3181df4521

14. Kibler WB, Press J, Sciascia A. The role of core stability in athletic function. *Sports Med*. 2006;36(3):189-198. doi:10.2165/00007256-200636030-00001

15. Moghadam N, Ghaffari MS, Noormohammadpour P, et al. Comparison of the recruitment of transverse abdominis through drawing-in and bracing in different core stability training positions. *J Exerc Rehabil*. 2019;15(6):819-825. doi:10.12965/jer.1939064.352

16. Matthijs OCG, Dedrick GS, James CR, et al. Co-contractive activation of the superficial multifidus during volitional preemptive abdominal contraction. *PM & R*. 2014;6(1):13-21. doi:10.1016/j.pmrj.2013.08.606

17. Lee SH, Kim TH, Lee BH. The effect of abdominal bracing in combination with low extremity movements on changes in thickness of abdominal muscles and lumbar strength for low back pain. *J Phys Ther Sci*. 2014;26(1):157-160. doi:10.1589/jpts.26.157

18. Maeo S, Takahashi T, Takai Y, Kanehisa H. Trunk muscle activities during abdominal bracing: comparison among muscles and exercises. *J Sports Sci Med*. 2013;12(3):467-474.

19. Vera-Garcia FJ, Elvira JLL, Brown SHM, McGill SM. Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. *J Electromyogr Kinesiol*. 2007;17(5):556-567. doi:10.1016/j.jelekin.2006.07.004

20. Portney LG, Watkins MP. *Foundations of Clinical Research: Applications to Practice*. 3rd ed. Prentice Hall; 2009.

21. Jamison ST, McNally MP, Schmitt LC, Chaudhari AMW. The effects of core muscle activation on dynamic trunk position and knee abduction moments: implications for ACL injury. *J Biomech*. 2013;46(13):2236-2241. doi:10.1016/j.jbiomech.2013.06.021

22. Marshall P, Murphy B. The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. *J Electromyogr Kinesiol*. 2003;13(5):477-489. doi:10.1016/s1050-6411(03)00027-0

23. Butler HL, Hubley-Kozey CL, Kozey JW. Electromyographic assessment of trunk muscle activation amplitudes during a simulated lifting task using pattern recognition techniques. *J Electromyogr Kinesiol*. 2009;19(6):e505-e512. doi:10.1016/j.jelekin.2008.09.010

24. Zaheer F, Roy SH, De Luca CJ. Preferred sensor sites for surface EMG signal decomposition. *Physiol Meas*. 2012;33(2):195-206. doi:10.1088/0967-3334/33/2/195

25. Blanc Y, Dimanico U. Electrode Placement in Surface Electromyography (sEMG) “Minimal Crosstalk Area” (MCA). *Open Rehabil J*. 2010;3(1):110-126. doi:10.2174/1874943701003010110

26. Beith ID, Synnott RE, Newman SA. Abdominal muscle activity during the abdominal hollowing manoeuvre in the four point kneeling and prone positions. *Man Ther*. 2001;6(2):82-87. doi:10.1054/math.2000.0376

27. Hooper TL, James CR, Brismée JM, et al. Dynamic balance as measured by the Y-Balance Test is reduced in individuals with low back pain: A cross-sectional comparative study. *Phys Ther Sport*. 2016;22:29-34. doi:10.1016/j.ptsp.2016.04.006

28. De Luca CJ. The Use of Surface Electromyography in Biomechanics. *J Appl Biomech*. 1997;13(2):135-163. doi:10.1123/jab.13.2.135

29. Zink AJ, Whiting WC, Vincent WJ, McLaine AJ. The effects of a weight belt on trunk and leg muscle activity and joint kinematics during the squat exercise. *J Strength Cond Res*. 2001;15(2):235-240.

30. DiStasio TJ. Validation of the Brzycki and Epley Equations for the 1 Repetition Maximum Back Squat Test in Division I College Football Players. 2014:40.

31. Smilios I, Häkkinen K, Tokmakidis SP. Power output and electromyographic activity during and after a moderate load muscular endurance session. *J Strength Cond Res*. 2010;24(8):2122-2131. doi:10.1519/jsc.0b013e3181a5bc44

32. Warren LP, Appling S, Oladehin A, Griffin J. Effect of soft lumbar support belt on abdominal oblique muscle activity in nonimpaired adults during squat lifting. *J Orthop Sports Phys Ther*. 2001;31(6):316-323. doi:10.2519/jospt.2001.31.6.316

33. Leardini A, Sawacha Z, Paolini G, Ingrosso S, Nativo R, Benedetti MG. A new anatomically based protocol for gait analysis in children. *Gait Posture*. 2007;26(4):560-571. doi:10.1016/j.gaitpost.2006.12.018

34. Cappozzo A, Catani F, Della Croce U, Leardini A. Position and orientation in space of bones during movement: anatomical frame definition and determination. *Clin Biomech*. 1995;10(4):171-178. doi:10.1016/0268-0033(95)91394-t

35. Dempster WT. *Space Requirements of the Seated Operator, USAF, WADC, Tech. Rep.*; 1955.

36. Introduction to Real World Statistics: With Step-By-Step SPSS Instructions, 1st Edition (Paperback) - Routledge. Routledge.com. Accessed October 20, 2019. https://www.routledge.com/Introduction-to-Real-World-Statistics-With-Step-By-Step-SPSS-Instructions/Vieira-Jr/p/book/9781138292307

37. Jull GA, Richardson CA. Motor control problems in patients with spinal pain: a new direction for therapeutic exercise. *J Manipulative Physiol Ther*. 2000;23(2):115-117. doi:10.1016/s0161-4754(00)90079-4

38. Grenier SG, McGill SM. Quantification of Lumbar Stability by Using 2 Different Abdominal Activation Strategies. *Arch Phys Med Rehab*. 2007;88(1):54-62. doi:10.1016/j.apmr.2006.10.014

39. Vera-Garcia FJ, Elvira JLL, Brown SHM, McGill SM. Effects of abdominal stabilization maneuvers on the control of spine motion and stability against sudden trunk perturbations. *J Electromyogr Kinesiol*. 2007;17(5):556-567. doi:10.1016/j.jelekin.2006.07.004

40. Schoenfeld BJ. Squatting kinematics and kinetics and their application to exercise performance. *J Strength Cond Res*. 2010;24(12):3497-3506. doi:10.1519/jsc.0b013e3181bac2d7

41. Matsumoto H, Suda Y, Otani T, Niki Y, Seedhom BB, Fujikawa K. Roles of the anterior cruciate ligament and the medial collateral ligament in preventing valgus instability. *J Orthop Sci*. 2001;6(1):28-32. doi:10.1007/s007760170021

42. Hattin HC, Pierrynowski MR, Ball KA. Effect of load, cadence, and fatigue on tibio-femoral joint force during a half squat. *Med Sci Sports Exerc*. 1989;21(5):613-618. doi:10.1249/00005768-198910000-00019

43. Donnelly DV, Berg WP, Fiske DM. The effect of the direction of gaze on the kinematics of the squat exercise. *J Strength Cond Res*. 2006;20(1):145-150. doi:10.1519/r-16434.1

44. Lavender SA, Li YC, Andersson GBJ, Natarajan RN. The effects of lifting speed on the peak external forward bending, lateral bending, and twisting spine moments. *Ergonomics*. 1999;42(1):111-125. doi:10.1080/001401399185838

45. Greenland KO, Merryweather AS, Bloswick DS. The effect of lifting speed on cumulative and peak biomechanical loading for symmetric lifting tasks. *Saf Health Work*. 2013;4(2):105-110. doi:10.1016/j.shaw.2013.04.001

46. Neumann D. *Kinesiology of the Musculoskeletal System: Foundations for Rehabilitation*. Elsevier; 2017.

47. Haddas R, Hooper T, James CR, Sizer PS. Volitional Spine Stabilization During a Drop Vertical Jump From Different Landing Heights: Implications for Anterior Cruciate Ligament Injury. *J Athl Train*. 2016;51(12):1003-1012. doi:10.4085/1062-6050-51.12.18

48. Hall L, Tsao H, MacDonald D, Coppieters M, Hodges PW. Immediate effects of co-contraction training on motor control of the trunk muscles in people with recurrent low back pain. *J Electromyogr Kinesiol*. 2009;19(5):763-773. doi:10.1016/j.jelekin.2007.09.008