Central Lancashire Online Knowledge (CLoK)

Title	Modelling Muscle Force Distributions during the Front and Back Squat in Trained Lifters
Type	Article
URL	https://clok.uclan.ac.uk/15273/
DOI	10.18276/cej.2016.2-02
Date	2016
Citation	Sinclair, Jonathan Kenneth, Atkins, Stephen, Vincent, Hayley and Richards, Jim (2016) Modelling Muscle Force Distributions during the Front and Back Squat in Trained Lifters. Cental European Journal of Sport Sciences and Medicine, 14 (2). pp. 13-20. ISSN 2300-9705
Creators	Sinclair, Jonathan Kenneth, Atkins, Stephen, Vincent, Hayley and Richards, Jim

MODELLING MUSCLE FORCE DISTRIBUTIONS DURING THE FRONT AND BACK SQUAT IN TRAINED LIFTERS

Jonathan Sinclair,[1, A, B, C, D] Stephen Atkins,[1, A, B, C, D] Hayley Vincent,[1, A, B, C, D] James D. Richards[2, A, B, C, D]

[1] Division of Sport Exercise and Nutritional Sciences, School of Sport and Wellbeing, University of Central Lancashire
[2] Allied Health Research Unit, School of Health Sciences, University of Central Lancashire
[A] Study Design; [B] Data Collection; [C] Statistical Analysis; [D] Manuscript Preparation

Address for correspondence:
Jonathan Sinclair
Division of Sport, Exercise and Nutritional Sciences
School of Sport Tourism and Outdoors
University of Central Lancashire,
Preston, Lancashire, PR1 2HE.
E-mail: Jksinclair@uclan.ac.uk

Abstract. The barbell squat is a fundamental strength and conditioning exercise, with two principal variants; back and front. Whilst previous studies have examined the mechanical differences of the front and back squat, there is no information comparing the distributions of muscle forces between these variants. This study aimed to compare estimated forces developed by the primary skeletal muscles used in the front and back squat. Twenty-five male participants were recruited with 6.24 ±2.21 years of experience in squat lifting and 1 repetition maximum values of 127.5 ±18.8 and 90.6 ±14.4 kg for the back and front squat lifts. Participants completed both back and front squats at 70% of their front squat 1 repetition maximum. Muscle forces were determined during dynamic situations using motion capture data, in addition to sagittal plane kinematics. Differences between squat conditions were examined using a multivariate analysis of variance. The kinematic analysis showed that the back squat was associated with significantly ($p < 0.05$) greater flexion of the trunk. Examination of muscles forces indicated that erector spinae forces were also significantly ($p < 0.05$) larger in the back squat. No significant differences were identified for skeletal muscle forces elsewhere ($p > 0.05$). Our results indicate that neither the front nor back squat provides any marked difference in muscle force production, aside from that isolated to the lower back. These findings lead the conclusion that neither the front nor back squat conditions confer any additional benefits over the other in terms of the skeletal muscle force output.

Key words: Biomechanics, resistance training, weight lifting

Introduction

Barbell squats are a principal lift in fundamental strength and conditioning (Clark, Lambert, Hunter, 2012). The purpose of the squat is to train and strengthen the muscles associated with the hip and knee joints (Wilk et al., 1996). The squat is representative of a closed kinetic movement and has been shown to closely represent a number

athletic and everyday motions (Escamilla et al., 1998; Wilk et al., 1996). It is traditionally represented as a central exercise in training routines designed to augment athletic performance and to enhance quality of life (Escamilla, 2001). The squat has two principal variants; back and the front squat lifts. Although both squat conditions are mechanically similar, variations may exist in terms of technique and muscular involvement (Russell, Phillips, 1989).

During the back squat, when the high bar position is utilized the lifter positions the bar superior aspect of the trapezius below the C7 spinous process (Baechle, Earle, 2008; Russell, Phillips, 1989). The back squat is accomplished by flexing the hip and knee joints until the thigh segment is parallel to the ground (Escamilla, 2001). Having achieved the required depth, the lifter then extends the hip and knee joints until the original standing position is attained. The front squat requires the lifter to place the barbell in an anterior position aligned with the clavicular ridge. When the clean grip is adopted the elbows are flexed and the shoulders are and internally rotated. This allows the upper arm segments to be positioned parallel to the ground (Baechle, Earle, 2008; Gullett, Tillman, Gutierrez, Chow, 2009). The phasic aspects of the descent and ascent of the front squat are identical to those in the back squat. Typically, the back squat is executed with the trunk in a more flexed position in relation to the front squat. This relates to the more posterior position of the barbell, whereby distal aspect of the trunk must be projected anteriorly in order to maintain balance during the lift (Baechle, Earle, 2008, Gullett et al., 2009).

There is an emerging body of research relating to the biomechanical properties of both squat variants. Russell, Phillips (1989) compared kinematics and knee extensor torque during the front and back squat lifts. No difference in knee torque was found between different squat conditions although the back squat increased trunk flexion which was attributed to the posterior position of the bar. It should be noted however that this study utilized an incorrect technique to determine the distal end of the trunk, which may have influenced the resultant trunk inclination. Diggin et al. (2011) examined the differences in trunk and lower limb kinematics between the front and back squat. Their findings confirmed previous findings that the back squat was associated with significantly greater trunk lean compared to the front squat. Stuart, Meglan, Lutz, Growney, An (1996) examined tibiofemoral joint forces and muscle activity during the front and back squat conditions using a low mass 50 lb barbell. They showed that neither tibiofemoral forces nor muscle activation differed significantly as a function of the different squat techniques. Similarly Gullett et al. (2009) examined tibiofemoral joint kinetics and activation of the quadriceps, hamstring and erector spinae muscles when performing the front and back squat lifts. They showed that the back squat resulted in larger tibiofemoral compressive forces and knee extensor moments than the front squat, although no differences in muscle activation were observed.

Whilst a comprehensive overview of the biomechanics of front and back squats has now emerged, there has yet to be a comparative examination of the muscles forces associated with the two squatting modalities, notably with regard to skeletal muscle force distributions. A lack of suitable measurement tools, used to determine dynamic muscle forces, is a key limitation.

Recently, specific software has been developed to estimate skeletal muscle force distribution during dynamic situations, using motion capture based data (Delp et al., 2007). To date, such estimations have not been reported with regard to dynamic activities, such as the squat. The aim of the current investigation was to examine the influence of the front and back squat variants on the forces produced by the different skeletal muscles. A study of this nature may provide important information for those involved in resistance training, providing evidence of the extent of recruitment for the key muscles associated with two widely used variants of the squat.

Methods

Participants

Twenty-five male participants (age 24.7 SD 4.4 years, height 1.7 SD 0.1 m and body mass 75.4 SD 5.2 kg), volunteered to take part in the current investigation. Participants had 6.24 ±2.21 years of experience in squat lifting with 1 repetition maximum values of 127.5 ±18.8 and 90.6 ±14.4 kg for the back and front squat lifts respectively. Participants trained at least 3 times per week and habitually utilized both squatting techniques as part of their resistance training routine. Ethical approval was obtained from the University Ethics Committee, and the procedures outlined in the Declaration of Helsinki were followed.

Procedure

Participants completed five repetitions in each squat condition, using their normal back and front squat technique. The load was consistent for both conditions, with participants lifting 70% of their front squat 1 repetition maximum. Participants completed their squats in a randomised order. To acquire ground reaction force information, the right foot was positioned onto a piezoelectric force platform (Kistler, Kistler Instruments Ltd., Alton, Hampshire) which sampled at 1000 Hz.

Kinematic information was captured at 250 Hz using an eight camera optoelectric motion analysis system (Qualisys™ Medical AB, Goteburg, Sweden). To define the anatomical frames of the trunk, pelvis, thighs, shanks and feet retroreflective markers were placed at the C7, T12 and xiphoid process landmarks and also positioned bilaterally onto the acromion process, iliac crest, anterior superior iliac spine, posterior super iliac spine, medial and lateral malleoli, medial and lateral femoral epicondyles and greater trochanter. Carbon-fibre tracking clusters comprising of four non-linear retroreflective markers were positioned onto the thigh and shank segments. Static calibration trials were obtained with the participant in the anatomical position in order for the positions of the anatomical markers to be referenced in relation to the tracking clusters/markers.

Data processing

Dynamic trials were digitized using Qualisys Track Manager in order to identify anatomical and tracking markers then exported as C3D files to Visual 3D (C-Motion, Germantown, MD, USA). Ground reaction force and kinematic data were smoothed using cut-off frequencies of 25 and 6 Hz with a non-phase shift low-pass Butterworth 4th order filter.

OpenSim software (Simtk.org) was used to quantify muscle forces during front and back squat lifts (Delp et al., 2007). Muscle force simulations were quantified using the standard gait2392 model using Opensim v3.2. This model corresponds to the eight segments exported from Visual 3D and had 19 total degrees of freedom. The trunk was considered to be a single segment capable of three planar rotations. The pelvis was associated with six degrees of freedom as it was able to rotate and translate in all three axes. The thigh segment was considered to possess three rotational degrees of freedom and was modelled as a ball and socket at its proximal end. The shank and foot segments were considered to possess a single (sagittal plane) rotational degree of freedom and modelled as hinge joint at their proximal ends.

The gait2392 model features ninety two muscles, eighty six of which are centred around the lower extremities and six are associated with the pelvis and trunk. The muscle properties were modelled using the Hill

recommendations based on the associations between force-velocity-length (Zajac, 1989). These muscle properties were then scaled based on each participant's height and body mass based on the recommendations of Delp et al. (1990). Following scaling a residual reduction algorithm (RRA) was utilized within OpenSim, this followed the inverse kinematics and ground reaction forces that were exported from Visual 3D. The RRA protocol works by calculating the net joint moments required to re-produce the dynamic motion. The RRA calculations performed on the experimental data all produced route mean squared errors of less than 2°, which corresponds with the recommendations provided by OpenSim for good quality data. Following the RRA, the computed muscle control (CMC) procedure was then employed to estimate a set of muscle force patterns allowing the model to replicate the required kinematics (Thelen, Anderson, Delp, 2003). The CMC procedure works by estimating the required muscle forces to match the net joint moment.

Following the CMC procedure peak and average forces during the squat movement were calculated for the Psoas Major, Iliacus, Gluteus Maximus, Biceps Femoris long head, Biceps Femoris short head, Semitendinosus, Semimembranosus, Rectus Femoris, Vastus Medialis, Vastus lateralis, Vastus intermedius, and Erector Spinae muscles from the right side. The timing of the initiation and termination of the squat movement for both techniques were taken as the instances of maximum hip extension in accordance with those of Sinclair, McCarthy, Bentley, Hurst, Atkins (2014). The net peak muscle force values (N) were normalized by dividing by the participants' body mass, allowing muscles forces to be expressed as N.kg.

Sagittal plane kinematic measures from the hip, knee and trunk which were extracted for statistical analysis were 1) peak angle during the squat and 2) angular excursion from initiation of movement to peak angle. Joint mechanics were computed as a function of the distal segment relative to the proximal segment (hip = thigh relative to pelvis, knee = shank relative to thigh, ankle foot relative to shank and trunk = trunk relative to pelvis). These variables were extracted from each of the five trials for each condition and the data was then averaged within subjects for statistical analysis. Participant's joint kinematic and curves were time normalized from 0–100% of the squat phase and were ensemble averaged across subjects for visual purposes only.

Statistical analyses

Differences in muscle forces and sagittal plane kinematics from each squat condition were examined using a multivariate analysis of variance with significance accepted at the $p < 0.05$ level (Sinclair et al., 2013). Follow up comparisons were utilized in order resolve significant differences between squat conditions. Effect sizes were calculated using a partial Eta^2 (pη^2). All statistical analyses were conducted using SPSS v22.0 (SPSS Inc., Chicago, USA).

Results

The overall multivariate analysis was significant F = 4.58, $p < 0.05$; Wilk's Λ = 0.245, pη^2 = 0.56. The results indicate that whilst the kinematic curves from the two conditions were qualitatively similar, squat technique significantly affected the outcome muscle kinetics and joint kinematics. Table 1–2 and Figure 1 present the muscle force distributions and joint kinematics obtained as a function of different squat techniques.

Joint kinematics

Peak trunk flexion was shown to be significantly greater (F = 14.57, p < 0.05, $p\eta^2$ = 0.39) in the back squat in comparison to the front squat (Figure 1). No significant differences (p > 0.05) in hip, knee and ankle joint kinematics were observed between the two conditions.
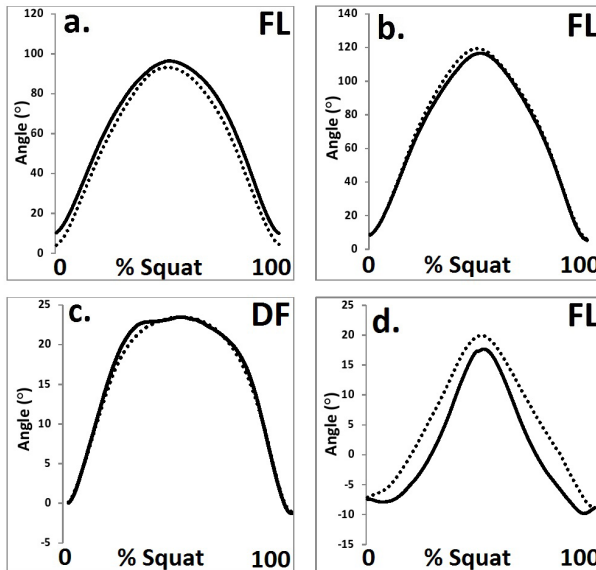
Figure 1. Sagittal plane kinematics of the a. hip, b. knee, c. ankle and d. trunk as a function of the different squat techniques (black = front, dot = back) (FL = flexion, DF = dorsiflexion)

Muscles forces

Peak force in the erector spinae was found to be significantly (F = 16.21, p < 0.05, $p\eta^2$ = 0.42) larger in the back squat. No further significant differences in muscles forces were observed between squat conditions (Table 1–2)

Table 1. Peak muscle force distributions as a function of the two squat techniques

Specification	Back squat		Front squat	
	Mean	SD	Mean	SD
1	2	3	4	5
Psoas Major (N.kg)	6.26	2.66	6.13	3.81
Iliacus (N.kg)	6.69	3.44	7.01	3.90
Gluteus maximus (N.kg)	11.24	1.71	10.54	2.87
Biceps Femoris long head (N.kg)	12.92	1.68	12.74	1.46
Biceps Femoris short head (N.kg)	4.86	3.31	4.69	2.59
Semitendinosus (N.kg)	4.98	1.15	4.76	1.22
Semimembranosus (N.kg)	17.91	1.33	17.87	2.09

1	2	3	4	5
Rectus Femoris (N.kg)	9.53	4.93	9.52	4.76
Vastus Medialis (N.kg)	12.45	3.76	12.54	2.42
Vastus Lateralis (N.kg)	21.18	6.18	22.20	3.88
Vastus Intermedius (N.kg)	13.61	4.17	13.30	2.68
Erector Spinae (N.kg)	22.30	5.09	16.46	4.53

Table 2. Average muscle force distributions as a function of the two squat techniques

Specification	Back squat		Front squat	
	Mean	SD	Mean	SD
Psoas Major (N.kg)	1.94	1.87	2.13	1.81
Iliacus (N.kg)	1.97	1.97	2.24	1.89
Gluteus Maximus (N.kg)	1.35	1.38	0.79	0.56
Biceps Femoris long head (N.kg)	7.25	1.79	5.80	1.27
Biceps Femoris short head (N.kg)	1.45	2.56	0.47	0.17
Semitendinosus (N.kg)	2.28	1.06	1.77	0.50
Semimembranosus (N.kg)	8.66	2.76	7.31	2.23
Rectus Femoris (N.kg)	2.96	2.97	2.96	2.94
Vastus Medialis (N.kg)	6.43	2.71	6.02	1.64
Vastus Lateralis (N.kg)	11.57	4.56	11.15	2.44
Vastus Intermedius (N.kg)	7.03	2.76	6.58	1.53
Erector Spinae (N.kg)	8.28	3.57	6.27	3.01

Discussion

The current study investigated the influence of the front and back squat techniques on the forces produced by the key skeletal muscles used in these lifts. This represents the first comparative investigation to examine differences in muscle force production during the front and back squat lifts.

The first key observation from the current investigation was in relation to the kinematic analysis. Flexion of the trunk was significantly greater when performing the back squat, in relation to the front squat. This finding concurs with the observations of both Russell, Phillips (1989) and Diggin et al. (2011) who noted similar increases in trunk flexion when performing the back squat. It is likely that this observation relates to the posterior position of the barbell during the back squat in relation to the front squat, thus the distal end of the trunk segment must be projected forwards to maintain balance.

A major innovation of the current study was to estimate skeletal muscle forces, associate with the performance of the front and back squat. Our findings showed that erector spinae muscle force was significantly larger in the back squat condition when compared to the front squat. It is likely that this finding relates to the increased flexion of the trunk segment during the back squat lift. Although not recognised as a dynamic flexor of the trunk segment, it is likely that the enhanced force output associated with this muscle is related to the increased eccentric force production in this muscle as a function of the increase trunk flexion. This observation opposes the EMG study of Gullett et al. (2009) who found no differences in erector spinae muscle activation between the two squat techniques.

Such conflicting findings may be due differences in techniques used between studies, as muscle forces quantified using inverse kinematic techniques are distinct from surface electromyograpic techniques.

An additional observation pertinent to the current investigation is that no differences in quadriceps or hamstring muscle forces were noted between the two squatting modalities. This observation concurs with those of Gullett et al. (2009) and Stuart et al. (1996) who also showed that lower extremity muscle recruitment measured using surface EMG did not differ between front and back squat conditions. Therefore these findings lead the conclusion that neither the front or back squat conditions confers any additional training benefits over the other in terms of the skeletal muscle force output. It is also pertinent to note that the similarity of findings, when using two very different methods, may justify the potential for the estimation of muscle forces method to be used further, when compared to more traditional assessments of muscle activation and engagement.

There are some limitations to the current investigation that it is important to acknowledge. That the current investigation utilized the same resistance for each squat condition means that the relative load was different for both conditions. This procedure was necessary; however, in the context of this study as the ground reaction force information serves as a key input parameter for the inverse kinematic procedure. Therefore, the same resistance was required in order to allow a fair comparison of muscle forces between conditions. This is important, as using a different resistance in each condition would alter the ground reaction force input as a function of the mass that was being lifted. Finally, that this study utilized a simulation based procedure to quantify muscles forces during the squat may also serve as a limitation. The efficacy of musculoskeletal simulations depends on the underlying mathematical model. Numerous mechanical assumptions are made in the construction of musculoskeletal simulation models (Delp et al., 1990). These predominately relate to the constrained rotational degrees of freedom at the knee and ankle joints and the lack of key muscles such as recuts abdominis, which may lead to incorrectly predicted muscle forces. However, as direct quantification of muscle forces are not possible at this time, the current procedure is the most practicable method of quantifying muscle forces in dynamic movements.

In conclusion, although previous analyses have comparatively examined the mechanics of front and back squat the current knowledge with regards to the differences in muscles forces between the two modalities is limited. The current investigation addresses this by providing a comparison of the muscle forces between the front and back squat lifts in the muscles pertinent to the squat lift. The current study shows that the back squat condition was associated with significantly greater forces in the erector spinae muscle, although no differences were shown in the lower extremity muscles. This indicates that neither the front nor back squat offers any benefits over the other in terms of the training stimulus that they provide for the muscles pertinent to the squat.

References

Baechle, T.R., Earle, R. (2008). *Essentials of Strength Training and Conditioning* (pp. 366–369). Champaign: Human Kinetics.

Clark, D.R., Lambert, M.I., Hunter, A.M. (2012). Muscle activation in the loaded free barbell squat: A brief review. *J Strength Cond Res*, 26: 1169–1178.

Delp, S.L. Loan, J.P., Hoy, M.G., Zajac, F.E., Topp, E.L., Rosen, J.M. (1990). An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. *IEEE Trans Biomed Eng*, 37: 757–767.

Delp, S.L., Anderson, F.C., Arnold, A..S, Loan, P., Habib, A., John, C.T., Thelen, D.G. (2007). OpenSim: open-source software to create and analyze dynamic simulations of movement. *IEEE Trans Biomed Eng*, 54: 1940–1950.

Diggin, D., O'Regan, C., Whelan, N., Daly, S., McLoughlin, V., McNamara, L., Reilly, A. (2011). A biomechanical analysis of front versus back squat: injury implications. *Port Journal Sport Sci*, 11: 643–646.

Escamilla, R.F., Fleisig, G.S., Zheng, N., Barrentine, S.W., Wilk, K.E., Andrews, J.R. (1998). Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc, 30: 556–569.

Escamilla, R.F. (2001). Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc*, 33: 127–141.

Gullett, J.C., Tillman, M.D., Gutierrez, G.M., Chow, J.W. (2009). A biomechanical comparison of back and front squats in healthy trained individuals. *J Strength Cond Res*, 23: 284–292.

Russell, P.J., Phillips, S.J. (1989). A preliminary comparison of front and back squat exercises. *Res Q Exercise Sport*, 60: 201–208.

Sinclair, J., Taylor, P.J., Hobbs, S.J. (2013). Alpha level adjustments for multiple dependent variable analyses and their applicability – A review. *Int Journal Sport Sci Eng*, 7: 17–20.

Sinclair, J., McCarthy, D., Bentley, I., Hurst, H.T., Atkins, S. (2014). The influence of different footwear on 3-D kinematics and muscle activation during the barbell back squat in males. *Eur J Sport Sci.* DOI: 10.1080/17461391.2014.965752.

Stuart, M.J., Meglan, D.A., Lutz, G.E., Growney, E.S., An, K.N. (1996). Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. *Am J Sports Med*, 24: 792–799.

Thelen, D.G., Anderson, F.C., Delp, S.L. (2003). Generating dynamic simulations of movement using computed muscle control. *J Biomech*, 36: 321–328.

Wilk, K.E., Escamilla, R.F., Fleisig, G.S., Barrentine, S.W., Andrews, J.R., Boyd, M.L. (1996). A Comparison of Tibiofemoral Joint Forces and Electromyographic Activity During Open and Closed Kinetic Chain Exercises. *Am J Sports Med*, 24: 518–527.

Zajac, F.E. (1989). Muscle and tendon: properties, models, scaling, and application to biomechanics and motor control. *Crit Rev Biomed Eng*, 17: 359–411.