KINETICS, KINEMATICS AND MUSCLE ACTIVATION DURING ECCENTRIC SQUATTING

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The purpose of this study was to examine the kinetics, kinematics and muscle activation of the knee and hip extensors during the eccentric (ECC) phase of the squat exercise. Resistance trained males (n=9) performed isotonic loaded ECC squats at loads from 20-150% of squat 1-rep max. Inverse dynamic calculations were used to identify knee and hip joint moment, and iEMG was used to quantify muscle activation of the vastus lateralis and gluteus maximus. In contrast to previous literature examining the concentric phase of the squat, this study found the knee extensors experienced the greatest loading, plateauing when exposed to a load of >120% of 1RM, with no changes in joint kinematics. Vastus lateralis iEMG plateaued after 80% of 1RM, suggesting activation-independent factors for this increase in joint moment. If maximising knee extensor loading to promote adaptation is a training object, this data recommends an ECC load of 120%.

KEYWORDS: Inverse Dynamics, Electromyography, Strength & Conditioning.

INTRODUCTION: The squatting exercise is one of the most commonly performed movements in strength and conditioning (S&C) and rehabilitation practices due to the synergistic flexion/extension of the knee, hip and ankle joints under load, which can promote skeletal muscle and neurological adaptation. However, due to the attenuation of skeletal muscle adaptations over time (Ahtiainen et al. 2003), S&C coaches are constantly exploring advanced training methodologies to allow further adaptation to occur. One method gaining in popularity is eccentric (ECC) based resistance training (Harden et al. 2020), with accentuated eccentric loading (AEL) (ECC load greater than 1-rep maximum) being a preferred method (Suchomel et al. 2019). AEL has been shown to produce superior increases in muscle mass and strength to traditional resistance training methods (equal CON & ECC load) (Roig et al. 2009). The increased loading in the ECC phase may increase mechanical tension within the sarcomere, which has a dose-response relationship with the activation of mTORC1 (Rindom et al. 2019), which is a key regulator in muscle hypertrophy. However, there are currently no guidelines on how best to prescribe loading for this method of resistance training.

A large body of literature has examined the kinetics and kinematics during the concentric (CON) phase of the squat (Schoenfeld 2010). As load increases, the CON joint angular velocities of the hips and knees decrease, and the CON joint moment increase, in a non-linear fashion (Farris et al. 2016). The relative contribution of the CON hip joint moment (to the sum of lower body moments) increases with load, and relative contribution of the CON knee joint moment decreases, with an eventual plateau in CON knee joint moment as load continues to increase (~80% 1-rep max) (1RM) (Flanagan and Salem 2008). Likewise, according to van den Tillaar (2019A), as load increases the CON muscle activation of the vastus lateralis (VL) and gluteus maximus (GM) increase in a non-linear fashion. Therefore, most guidelines suggest a loading of 80% during the CON phase, as this should maximise mechanical tension of the knee extensors.

However, due to the complexity of performing eccentric movements owing to the unique neural activation strategies during ECC contraction (Duchateau and Enoka 2016), the technical strategies used to perform the ECC phase of the squat (van den Tillaar 2019B), and the attenuation of force due to the titin protein within the sarcomere (Herzog 2018), it is unknown if these relationships hold true during the ECC squatting phase. Therefore, the purpose of this study was to investigate the effect of load on the kinetics, kinematics, and muscle activation during the ECC phase of squatting, using both traditional loading paradigms (<100% 1RM) and AEL paradigms (>100%).

METHODS: Nine resistance trained males (age; 24 ± 2 years, body mass; 81.2 ± 8.6 kg, height; 178 ± 5 cm, squat 1RM relative to body mass; 1.71 ± 0.17) volunteered for this study. Participants were informed of the study procedures and gave written informed consent. All squatting exercises were performed on the Kineo Training System (v7, GLOBUS, Italy), to a depth where the thigh was parallel to the ground. All participants were familiar with performing squatting on this apparatus. Seven days prior to experimental data collection, participants performed a 1RM assessment, adhering to guidelines set by the NSCA (Haff and Triplett 2015). Participants performed ECC isotonic loaded squats on the Kineo Training System under 10 loading conditions in a randomised order (20, 40, 60, 80, 100, 110, 120, 130, 140, & 150% of CON 1RM). Three trials were performed for each loading condition, with three minutes rest between each trial. Participants were asked to self-select an appropriate descent velocity for each load. Mean data of the three trials at each load were used for analyses. Ground reaction forces (2000Hz) from two force plates (9287c, Kistler, Switzerland) were combined with motion capture data (using a modified CODA marker set, with additional tracking markers on the iliac crest) collected from six 3D motion capture cameras (200 Hz) (Opus 3 series, Qualisys, Sweden). Data was collected in QTM software (Qualisys, Sweden) and then exported to Visual3D (C-Motion, USA) to calculate joint moments ($N \cdot m \cdot kg^{-1}$) of the hip and knee joint, via inverse dynamics calculations, and to quantify joint angle (°) and joint velocity ($° \cdot s^{-1}$). Force and motion data were processed with a 4^{th} order Butterworth filter, with a cut off frequency of 6 Hz. Electromyographic (EMG) signals obtained from the VL and GM, were transmitted (Research DTS, Noraxon, USA) and synchronised with motion data in Visual3D, band pass filtered (10/250 Hz) and then averaged using an RMS with moving average of 100ms. EMG data was normalised against a CON 100% 1RM trial, data is reported as an integrated EMG (iEMG). All data was checked for sphericity, homogeneity of variance and normality, before undergoing a one-way repeated measures ANOVA with Bonferroni post-hoc analysis to assess for differences between each eccentric load for each outcome measure.

RESULTS: As load increased, peak ECC knee joint moment and peak ECC hip joint moment increased (F=16.408, P<0.001, F=12.773, P=0.007, respectively). However, post-hoc analyses found, there was no further significant increase in peak ECC knee moment after a load of 120% (P=0.045), and no further significant increase in peak ECC hip moment after a load of 80% (P=0.039) (Figure 1). ECC VL iEMG increased as load increased (F=2.233, P<0.028) with no further increase past 80%. Likewise, ECC GM iEMG increased as load increased (F=4.161, P<0.001) with no further increase past 100% (Figure 2). Range of motion did not differ with load for either the knee (F=0.276, P=0.979) (108 ± 6° to 112 ± 8°) or hip (F=0.274, P=0.98) (88 ± 10° to 93 ± 14°). The joint angle at which peak moment occurred remained constant for all trails (Knee: F=5.228, P=0.052 (98 ± 14° to 101 ± 11°). Hip: F=7.03, P=0.426 (79 ± 10° to 81 ± 12°). Finally, both ECC knee (58 ± 28°$\cdot s^{-1}$ to 63 ± 16°$\cdot s^{-1}$) and hip joint velocity (44 ± 13°$\cdot s^{-1}$ to 52 ± 15°$\cdot s^{-1}$) did not differ with increases in load (F=1.758, P=0.090; F=1.560, P=1.42, respectively).

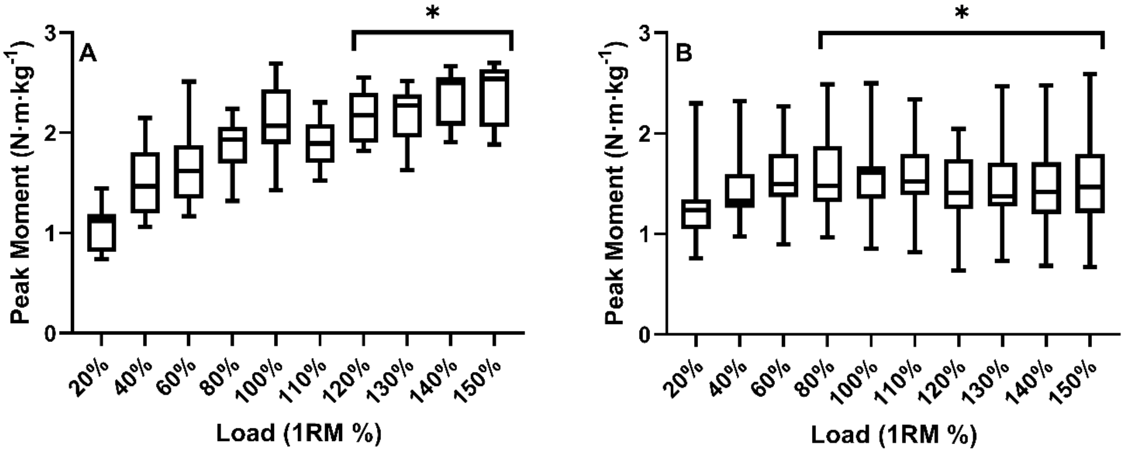

Figure 1: Peak ECC knee (A) and hip (B) joint moments (N·m·kg^{-1}) during ECC squatting at loads from 20-150% of 1RM. * signifies a plateau in joint moment, with no significant changes

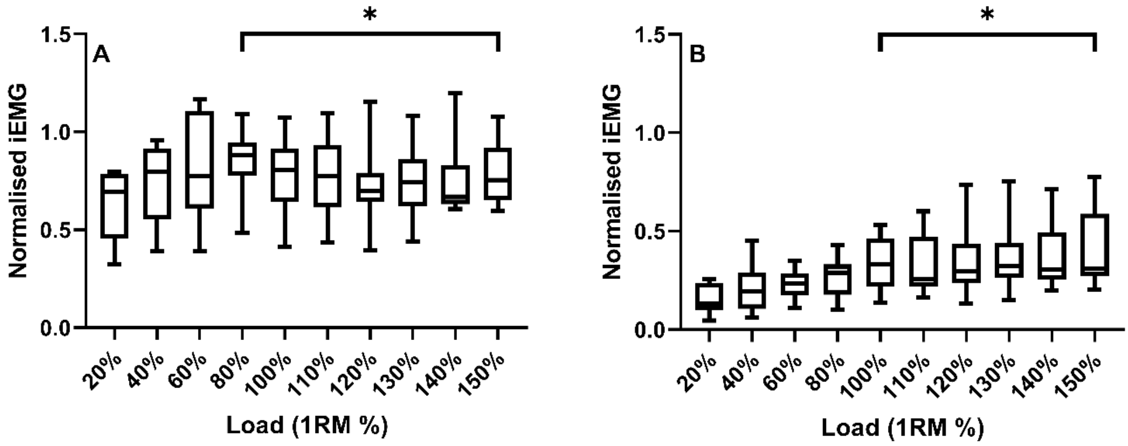

Figure 2: Normalised iEMG for the vastus lateralis (A) and gluteus maximus (B) during ECC squatting at loads from 20-150% of 1RM. * signifies a plateau in iEMG, with no significant changes

DISCUSSION: This study examined the kinetics and kinematics of the knee and hip joint, and the muscle activation of the VL and GM during the ECC phase of the squat under loads up to 150% of squat 1RM. Ranges of motion and ECC velocity remained constant regardless of load. However, ECC knee moment and hip moment, increased with load. ECC knee moment and hip moment plateaued at loads of 120% and 80%, respectively. Lastly, ECC VL iEMG and GM iEMG both increased with load, plateauing at loads of 80% and 100%, respectively.
As expected, both ECC knee and hip moment increased as load increased. However, our data contrasts previous studies which investigated the CON phase of the squat (Farris et al. 2016, Flanagan and Salem 2008). In the present study, ECC knee moment increased up to loads of 120% of 1RM, whilst the ECC hip moment only increased up to loads of 80% of 1RM. This resulted in a greater ECC knee moment at all loads (except 20%) than ECC hip moment (Figure 1). Conversely, previous studies have shown this to be the opposite in the CON phase (Farris et al. 2016, Flanagan and Salem 2008), with hip moment being greater than knee moment. Although these previous studies were performed with a barbell back squat, pilot work from our lab has identified no kinematic or muscle activation differences between performing ECC squatting on the Kineo Training System and with a barbell. This suggests that the ECC

phase of the squat preferentially loads the knee extensors, rather than hip extensors. This increased loading of the knee extensors is further amplified with the use of AEL, with an optimal load of 120% 1RM maximising ECC knee joint moment. Examination of the ECC knee moment profiles reveal that as load increases the time course of moment development changed, with an earlier onset of moment increase as load is increased. Suggesting not only is peak moment greater, and thus mechanical tension, but also the duration of mechanical tension.

Examination of the muscle activation reveals that VL iEMG plateaued at 80%, despite joint moment of the knee continuing to increase until 120%. The iEMG for the VL was ~70% of the CON 1RM iEMG (for which it was normalised against), compared to ~35% for the GM (figure 2), this further supports the preferential loading of the knee extensors during the ECC phase of the squat. Due to the increase in knee moment, despite changes in activation of the VL, this suggests factors independent of neural activation are responsible for the increased knee moment. Previous research has shown the spring-like titin protein is a plausible reason for this activation-independent increase in muscle force (Herzog 2018).Titin binds to both actin and the Z-disc, stored elastic energy (and interactions with Ca+) enable titin to stiffen the sarcomere, increasing force potential. Therefore, using an ECC load of 120% (AEL) would likely lead to a greater training stimulus for skeletal muscle adaptation than traditional ECC loading (e.g. 80%), but may not have an effect on neuromuscular adaptation.

CONCLUSION: Increasing ECC load during the squat does not alter squatting kinematics, with ranges of motion and ECC decent velocity remaining constant. Both the knee and hip ECC joint moments increase with load, with the knee experiencing a greater ECC moment under all loads than the hip. This in the opposite of what occurs during the CON phase of a squat, therefore suggesting a preferential overload of the knee extensors during ECC squatting. Examination of the muscle activations found iEMG increased with load, plateauing at 80% for the VL, suggesting activation-independent factors for the increased ECC knee moment. If the goal of a squat intervention is to maximise loading of the knee extensors, an ECC load of 120% appears to be optimal. Future research is required to confirm if this increased loading translates to increased skeletal muscle adaptation.

REFERENCES

Ahtiainen, J. P., A. Pakarinen, M. Alen, W. J. Kraemer & K. Häkkinen (2003) Muscle hypertrophy, hormonal adaptations and strength development during strength training in strength-trained and untrained men. *European journal of applied physiology,* 89**,** 555-563.

Duchateau, J. & R. M. Enoka (2016) Neural control of lengthening contractions. *J Exp Biol,* 219**,** 197-204.

Farris, D. J., G. A. Lichtwark, N. A. Brown & A. G. Cresswell (2016) Deconstructing the power resistance relationship for squats: A joint-level analysis. *Scand J Med Sci Sports,* 26**,** 774-81.

Flanagan, S. P. & G. J. Salem (2008) Lower extremity joint kinetic responses to external resistance variations. *J Appl Biomech,* 24**,** 58-68.

Haff, G. G. & N. T. Triplett. 2015. *Essentials of strength training and conditioning 4th edition*. Human kinetics.

Harden, M., C. Bruce, A. Wolf, K. M. Hicks & G. Howatson (2020) Exploring the practical knowledge of eccentric resistance training in high-performance strength and conditioning practitioners. *International Journal of Sports Science & Coaching,* 15**,** 41-52.

Herzog, W. (2018) The multiple roles of titin in muscle contraction and force production. *Biophys Rev,* 10**,** 1187-1199.

Rindom, E., A. M. Kristensen, K. Overgaard, K. Vissing & F. V. de Paoli (2019) Activation of mTORC1 signalling in rat skeletal muscle is independent of the EC-coupling sequence but dependent on tension per se in a dose-response relationship. *Acta Physiol (Oxf),* 227**,** e13336.

Roig, M., K. O'Brien, G. Kirk, R. Murray, P. McKinnon, B. Shadgan & W. D. Reid (2009) The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med,* 43**,** 556-68.

Schoenfeld, B. J. (2010) Squatting kinematics and kinetics and their application to exercise performance. *The Journal of Strength & Conditioning Research,* 24**,** 3497-3506.

Suchomel, T. J., J. P. Wagle, J. Douglas, C. B. Taber, M. Harden, G. G. Haff & M. H. Stone (2019) Implementing eccentric resistance training—Part 1: A brief review of existing methods. *Journal of Functional Morphology and Kinesiology,* 4**,** 38.
van den Tillaar, R. (2019) Effect of Descent Velocity upon Muscle Activation and Performance in Two-Legged Free Weight Back Squats. *Sports (Basel),* 7.
van den Tillaar, R., V. Andersen & A. H. Saeterbakken (2019) Comparison of muscle activation and kinematics during free-weight back squats with different loads. *PLoS One,* 14**,** e0217044.