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Effects of four different relative loads on knee joint kinetics during the barbell back squat.

Mechanics of different relative squat loads.

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***Abstract*—The barbell squat is fundamental in strength and conditioning. Unfortunately, the propensity for injury is high particularly at the knee. The aim of the current investigation was examine the influence four different relative squat loads (40, 50, 60 and 70 % 1 repetition maximum) on the forces experienced by the patellofemoral joint and patellar tendon. Patellofemoral and patellar tendon loads were obtained from twenty-five experienced male participants. Differences between squat conditions were examined using repeated measures ANOVA (p<0.0125). Significant increases (p<0.0125) in patellofemoral and patellar tendon forces were identified in the 60 and 70 % 1 repetition maximum conditions. It may be prudent therefore for lifters who are predisposed to patellofemoral and patellar tendon injuries to utilize lower relative squat loads to reduce their risk from knee pathology.**

Keywords: Biomechanics, squat, engineering

I. INTRODUCTION

The barbell back squat is a central exercise in the arena of strength and conditioning (1). This exercise serves to actively recruit the quadriceps, hamstrings, gluteus and gastrocnemius muscle groups (2, 3). The barbell squat is representative of a multi-joint closed chain movement and is recognised as the most functional weight training exercise (4).

However due to the mechanics of the barbell squat which is associated with high levels of knee flexion the propensity for injury is high, in particular at the knee joint itself (5). Patellofemoral pain syndrome (PFPS) is the most frequently encountered chronic pathology in athletic populations (6). PFPS is linked to overloading of the patellofemoral articulation during dynamic activities such as the squat which utilize high levels of knee flexion (7). PFPS can be debilitating, and may also serve as a pre-cursor to the aetiology of osteoarthritis in later life (8). In addition to patellofemoral pathology, squat exercises have been shown to place high demands on the patellar tendon (9). Patellar tendinopathy is a common pathology encountered in sports medicine, characterized by activity-related, anterior knee pain and localized patellar tendon tenderness (10). Much like PFPS patellar tendinopathy is considered to result from repeated overloading loading of the knee extensor mechanism during flexion based activities (11).

Given the potential propensity for musculoskeletal injury it is important to better understand the forces that are produced through the patellofemoral joint and patellar tendon when different squat loads are utilized. Previous analyses have considered the biomechanical variations when squatting with different loads. Wallace et al., (12) examined the effects of minimally loaded (35 % bodyweight) and bodyweight squats on knee extensor and patellofemoral kinetics. They showed that patellofemoral kinetics were significantly higher in the loaded condition. Bryanton et al., (13) investigated the effects of different squat depths and loads on hip, knee and ankle moments. Knee extensor moments were shown to increase with greater squat depth but not barbell load, whereas the opposite was found for the ankle plantarflexor moment. Their results also confirmed that both squat depth and barbell load increased hip extensor moments. There is currently no available published research that has considered the forces experienced by the patellofemoral joint and patellar tendon when squatting using different relative loads.

The aim of the current investigation was therefore to examine the influence of different relative squat loads (40, 50, 60 and 70 % 1 repetition maximum (1RM) on the forces experienced by the patellofemoral joint and patellar tendon. A study of this nature may provide important clinical information to those who habitually engage in squatting activities, regarding their susceptibility to patellofemoral and patellar tendon pain symptoms when performing the back squat lift at different relative intensities. This study tests the hypothesis that patellofemoral and patellar tendon forces will be greater when performing the back squat using higher relative loads.

2. METHODS

2.1 Participants

Twenty-five male participants (age 25.4 SD 4.6 years, height 1.7 SD 0.1 m and body mass 74.9 SD

4.7 kg), volunteered to take part in the current investigation. Participants had 5.16 ± 2.12 years of experience in squat lifting with 1 RM maximum values of 128.1 ± 19.2 for the back squat. All were free from musculoskeletal pathology at the time of data collection and provided written informed consent. The procedure utilized for this investigation was approved by the University of Central Lancashire, ethical committee in accordance with the principles outlined in the Declaration of Helsinki.

2.2 Procedure

Participants completed five repetitions in each squat condition. Participants lifted 40, 50, 60, and 70 % of their back squat 1 RM. To avoid any order effects, participants completed their squats in each of the four conditions a randomised order. To acquire knee joint kinetic 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^{TM} Medical AB, Goteburg, Sweden). The calibrated anatomical systems technique (CAST) was utilised to quantify knee joint kinematics (14). To define the anatomical frames of the right shank and thigh, retroreflective markers were positioned onto the 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.

2.3 Data processing

Ground reaction force and marker trajectories were filtered at 50 and 6 Hz using a low pass Butterworth 4th order zero-lag filter and analysed using Visual 3D (C-Motion, Germantown, MD, USA). Kinematics of the knee were quantified using an XYZ cardan sequence of rotations (where X = sagittal plane; Y = coronal plane and Z = transverse plane). Knee kinetic and kinematic curves were normalized to 100% of the squat movement. 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 et al., (15). Joint moments were computed using Newton-Euler inverse-dynamics. The net joint moments were subsequently normalized to participants' body mass and (Nm.kg).

Patellofemoral contact force (PTCF) (B.W) was estimated using knee flexion angle (KFA) and knee extensor moment (KXT) through the biomechanical model of Ho et al., (16). The moment arm of the quadriceps (QMF) was calculated as a function of KFA using a non-linear equation, based on cadaveric information presented by van Eijden et al., (17):

$$QMF = 0.00008\ KFA^3 - 0.013\ KFA^2 + 0.28\ KFA + 0.046$$

Quadriceps force (FQ) was calculated using the below formula:

$$FQ = KXT / QMF$$

PTCF was estimated using the QF and a constant (KN):

$$PCF = FQ\ KN$$

The KN was described in relation to KFA using a curve fitting technique based on the non-linear equation described by van Eijden et al., (17):

$$KN = (0.462 + 0.00147\ KFA^2 - 0.0000384\ KFA^2) / (1 - 0.0162\ KFA + 0.000155\ KFA^2 - 0.000000698\ KFA^3)$$

Patellofemoral pressure (PCP) (Mpa) was calculated using the PTCF divided by the patellofemoral contact area. The contact area was described using the Ho et al., (16) recommendations by fitting a 2nd-order polynomial curve to the data of Powers et al., (18) showing patellofemoral contact areas at varying levels of KFA.

$$PCP = PTCF / \text{contact area}$$

To estimate patellar tendon kinetics a predictive algorithm was utilized (19). Patellar tendon load (PTF) was determined by dividing the knee extensor moment (KXM) by the estimated patellar tendon moment arm (ptMA). The moment arm was quantified as a function of the sagittal plane knee angle by fitting a 2nd-order polynomial curve to the data provided by (20) showing patellar tendon moment arms at different KFA's.

$$PTF = KXM / ptMA$$

2.4 Statistical analyses

Differences in knee loading parameters across the four relative squat load conditions were examined using one-way repeated measures ANOVAs. The alpha criterion for statistical significance adjusted to $p = 0.0125$ using a Bonferroni correction to control type I error. Effect sizes were calculated using Eta^2 (η^2). Post-hoc pairwise comparisons were conducted on all significant main effects. The data was screened for normality using a Shapiro-Wilk which confirmed that the normality assumption was met. All statistical actions were conducted using SPSS v22.0 (SPSS Inc., Chicago, USA).

3. RESULTS

Figure 1 and tables 1 present the knee kinetics obtained as a function of different relative squat weights. The results indicate that different squat weights significantly influenced knee loading parameters.

Table 1: Patellofemoral and patellar tendon kinetics as a function of different relative squat loads.

	40% 1RM		50% 1RM		60% 1RM		70% 1RM		
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	
Peak KXT (Nm.kg)	1.67	0.75	1.84	0.82	2.03	0.91	2.09	0.90	*
Peak PTCF (B.W)	3.89	1.72	3.97	1.75	4.48	1.98	4.53	1.95	*
Peak PCP (Mpa)	5.56	2.40	5.73	2.47	6.15	2.73	6.19	2.76	*
Peak PTF (B.W)	5.76	2.52	6.54	2.88	7.12	3.05	7.38	3.29	*

Notes: * = significant difference

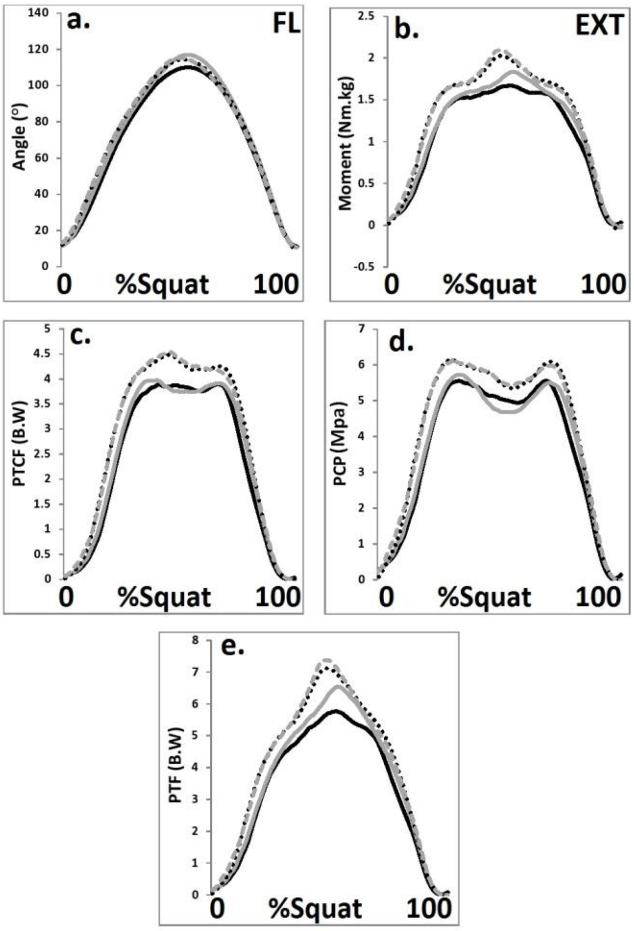

Figure 1: Knee kinetics and kinematics as a function of different squat loads, grey dash = 70 %, black dot = 60 %, grey = 50 % and black = 40 %. (a = sagittal knee angle, b = sagittal knee moment, c =PTCF, d = PCP, e = PTF) (FL = flexion and EXT = extension).

A significant main effect ($p<0.0125$, $\eta^2 = 0.49$) was observed for the peak KXM. Post-hoc pairwise comparisons showed that peak KXM was significantly greater in the 70 and 60 % 1RM conditions in comparison to the 40 and 50 % 1RM loads (Table 1; Figure 1b). A significant main effect ($p<0.0125$, $\eta^2 = 0.52$) was also found for the peak PTCF. Post-hoc pairwise comparisons showed that peak PTCF was significantly greater in the 70 and 60 % 1RM conditions in comparison to the 40 and 50 % 1RM loads (Table 1; Figure 1c). Furthermore, a significant main effect ($p<0.0125$, $\eta^2 = 0.51$) was observed for the peak PCP. Post-hoc pairwise comparisons showed that peak PCP was significantly greater in the 70 and 60 % 1RM conditions in comparison to the 40 and 50 % 1RM loads (Table 1; Figure 1d). Finally a significant main effect ($p<0.0125$, $\eta^2 = 0.57$) was shown for the peak PTF. Post-hoc pairwise comparisons showed that peak PTF was significantly greater in the 70 and 60 % 1RM conditions in comparison to the 40 and 50 % 1RM loads (Table 1; Figure 1e).

4. DISCUSSION

The current investigation aimed to examine the influence of different relative squat loads (40, 50, 60 and 70 % 1RM) on the forces experienced by the patellofemoral joint and patellar tendon. To the authors knowledge this represents the first study to explore the effects of different relative loads on the forces experienced by the knee joint during the barbell back squat exercise.

The first key finding from the current study supports our hypothesis in that patellofemoral kinetics both PTCF and PCP were shown to be significantly larger in the 60 and 70 % 1RM conditions in comparison to the lower relative loads. This observation concurs with those provided by Wallace et al., (12) who showed that performing the squat with a minimal load produced greater patellofemoral forces in comparison to squatting with no load. It is likely that this observation relates to the fact that increased loads place additional demands on the knee extensors which are the dominant muscle group associated with the squat movement (21). The KXT is a key input parameter into the quantification algorithm for PTFC and PCP therefore it appears that the increased knee extensor demands as a function of the greater squat loads also facilitated increases in PTCF and PCP.

This observation may have clinical relevance and provide insight into the mechanisms by which different squat loads may influence the aetiology of PTPS in weightlifters. The aetiology and progression of PTPS symptoms are considered to be a function of habitual and excessive loads experienced by the patellofemoral joint itself (16). This study therefore indicates that those who habitually utilize higher squat loads may be at increased risk from patellofemoral degradation.

A further important finding from this investigation is that patellar tendon forces were also shown to be larger in the 70 and 60 % 1RM conditions in comparison to the lower squat loads. This finding is also in agreement with those of Wallace et al., (12).This observation may also be relevant clinically as high patellar tendon loading are believed to be causative factors of patellar tendinopathy (11). These results therefore indicate that lifters who habitually use high squat loads may be more susceptible to developing patellar tendinopathy as a function of higher patellar tendon loading.

The findings from this study allow clinical recommendations to be made to weightlifters and those who habitually use the barbell back squat as part of their training. It is clear from the findings of this work that higher relative squat loads increase the loads experienced by the patellofemoral joint and the patellar tendon. However we do not advocate a universal policy of avoiding the utilization of heavy squatting, given the functional nature of the squat and its unique ability to recruit the lower extremity musculature (21). However for athletes/ weightlifters that are either susceptible to knee pathology or recovering from injury it may be prudent either to avoid heavy squat lifting or to utilize a reduced relative weight until their injury has healed.

In conclusion, although previous analyses have comparatively examined the mechanics of squatting using different loads the current knowledge with regards to the differences in patellofemoral and patellar tendon loads between is limited. The current investigation addresses this by providing a comparison of patellofemoral forces when squatting with different relative loads. The current study shows that higher relative squat loads were associated with significant increases in patellofemoral and patellar tendon kinetic parameters. Given the proposed relationship between the magnitude of the load experienced by the patellofemoral joint and the patellar tendon and knee pathology, it is suggested that the risk from developing knee injuries is greater when larger squat loads are lifted. Therefore it is recommended that those who are susceptible to knee pathologies or returning from injury utilize lower relative squat loads to attenuate their injury risk.

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