HIP MOMENT INCREASES WHILE KNEE AND ANKLE MOMENTS REMAIN CONSTANT DURING SQUATS WITH INCREASING LOADS IN ELITE POWERLIFTERS

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This study aimed to investigate compensation strategies among elite powerlifters under high-load conditions. 31 top-ranked powerlifters from the Austrian team executed competition-style squats at 70%, 75%, 80%, 85%, and 90% of their estimated 1-repetition-maximum (F_{max}). Employing musculoskeletal modelling, we conducted a biomechanical analysis (i.e. joints moments calculated via inverse dynamics) to understand the alterations in squatting mechanics across various loads. Our findings revealed a consistent relative load shift from the knee to the hip joint with increasing intensity. The knee and ankle joint moments remained constant from 70% to 90% F_{max}, underscoring the dominant role of the hip joint in high-load squatting, which indicates that an increasing external load imposes varying relative loads on the hip, knee, and ankle joints during squats.

KEYWORDS: squatting, powerlifting, inverse dynamics, compensation strategies

INTRODUCTION: The biomechanics of squat exercises have been a focal point of research within the realm of sports science, particularly in the context of building strength and hypertrophy of the knee and hip extensor muscles (Ribeiro et al., 2022). The increasing prominence of powerlifting, where the squat additionally to the bench press and deadlift constitutes one of the three competition lifts, has intensified inquiries from coaches and researchers on biomechanical optimization for enhancing the performance in this lift (Escamilla et al., 2001). Among the multifaceted factors influencing squat performance, the intricate interplay between joint kinematics and kinetics, muscle activation patterns, and neuromuscular control has captured the attention of researchers seeking to unravel the reason for compensation strategies (i.e., shifting the load to more capable joints) occurring during this fundamental movement (Larsen et al., 2021). Attaining insights into the dynamic underpinnings of these load-shifting strategies displayed by elite athletes during squat execution, with a particular focus on the hip, knee, and ankle joints is of utmost importance for increasing performance and reducing injuries in the short and long run (Sigward et a., 2018; Tateuchi et al., 2021). Understanding the relative joint moments during high load exercises enables coaches to tailor the technique of the squat to the athletes' current strength ratios and, in the long term, address muscular weaknesses through a purposeful and individually crafted training program. In the examination of the squat, both the knee and the hip joint are frequently the key areas of focus, resulting in differing assumptions regarding which joint is closer to its capacity to support high loads. (Beardsley et al., 2014; Bryanton et al., 2014; Bryanton et al., 2015). To date, however, no study has assessed this question within a group of elite powerlifting athletes. Therefore, the aim of this study was to quantify absolute and relative hip, knee, and ankle joint moments during squats with varying intensities, aiming to identify primary load-supporting joints in athletes during squatting. We hypothesized that absolute joint moments would increase while relative joint moments would remain constant among the hip, knee, and ankle joints as external loads during squats increased. If this hypothesis were confirmed, it would underscore the importance of a consistent and optimal technique in high-level powerlifting athletes, tailored to their individual strengths and weaknesses, irrespective of intensity. Such insights are crucial for coaches, providing valuable guidance to athletes in refining their technique, offering pertinent information for their training regimen, and ultimately enhancing their squat performance.

METHODS: 31 elite powerlifters (13 females, 18 males, 418.6±41.4 Wilks Score, 25.9±5.3 years), who were active members of the Austrian national powerlifting team or achieved a topthree ranking in an Austrian championship between 2019 and 2022, were recruited for this study. The participants provided written informed consent prior to their involvement. After individual warm-up procedures, each participant performed one squat at 70%, 75%, 80%, 85%, and 90% of their F_{max} regarding to the rules of the International Powerlifting Federation (IPF, 2024). Resting times between attempts were self-selected to ensure optimal individual preparation. Ground-reaction force from two force plates (Kistler Instruments AG, CH) and trajectories of 30 lower limb markers were recorded simultaneously, using a three-dimensional motion capture system (Vicon Motion System, Oxford, UK). Musculoskeletal simulations were performed using OpenSim 4.2 (Delp et al., 2007). The "Catelli"-model (Catelli et al., 2019), which is a validated model for high hip and knee flexion, was scaled to participants' anthropometry based on the location of surface markers (Kainz et al., 2017). The model included three degrees of freedom at the hip and knee, as well as two degrees of freedom at the ankle joint. Joint angles were calculated via inverse kinematics. Afterwards, joint moments were calculated using inverse dynamics, low pass filtered (6 Hz butterworth 4^{th} order) time normalized to 101 datapoints for eccentric (ECC) and concentric (CON) phases separately and averaged over left and right leg. Absolute joint moments (AJM) per load (70% - 90%F_{max}) were quantified as shown in equation (1), where subscript *joint* indicates either the hip, knee, or ankle joint in the sagittal plane. Subsequently, we calculated the relative contribution of each joint (RJM) to the total sagittal moment, as shown in equation (2).

Equation (1) $AJM_{joint} = mean\ (|moment_{joint}|)$

Equation (2) $RJM_{joint} = \frac{AJM_{joint}}{AJM_{hip}+AJM_{knee}+AJM_{ankle}} \times 100$

A two-way repeated measures ANOVA was used to assess the effects of phases (ECC, CON) and loads (70% - 90%F_{max}) on AJM and RJM. Subsequent post-hoc pairwise comparisons, were conducted using the Bonferroni correction. All statistical analyses were performed in JASP (version 0.18.1.0), with a significance level of 0.05.

RESULTS: Both the absolute ankle plantar-/dorsiflexion and absolute hip flexion/extension moment demonstrated a significant distinction between ECC and CON (ankle: $p<0.001$, $\eta^2_p=0.629$; hip: $p<0.001$, $\eta^2_p=0.823$), as well as among different intensity levels (ankle: $p<0.001$, $\eta^2_p=0.169$; hip: $p<0.001$, $\eta^2_p=0.874$; Figure 1). Post-hoc tests highlighted a noteworthy increase in absolute hip flexion/extension moment from 70% to 90%F_{max} during both ECC and CON ($p<0.001$, $\eta^2_p=0.214$). Absolute ankle plantar-/dorsiflexion moment, on the other hand, exhibited an increase during ECC between 70% and 80%F_{max} ($p=0.007$, $\eta^2_p=0.169$), 70% and 85%F_{max} ($p<0.001$, $\eta^2_p=0.169$), and 70% and 90%F_{max} ($p<0.001$, $\eta^2_p=0.169$), and no discernible differences in the CON phase. The absolute knee flexion/extension moment showed significance, only concerning intensity levels ($p<0.001$, $\eta^2_p=0.164$), with no variance noted between the ECC and CON phases. Further post-hoc comparisons indicated no disparities during the CON phase across different intensities but significantly higher moments at 70% compared to either 85%F_{max} or 90%F_{max} during the ECC phase ($p<0.001$, $\eta^2_p=0.228$).

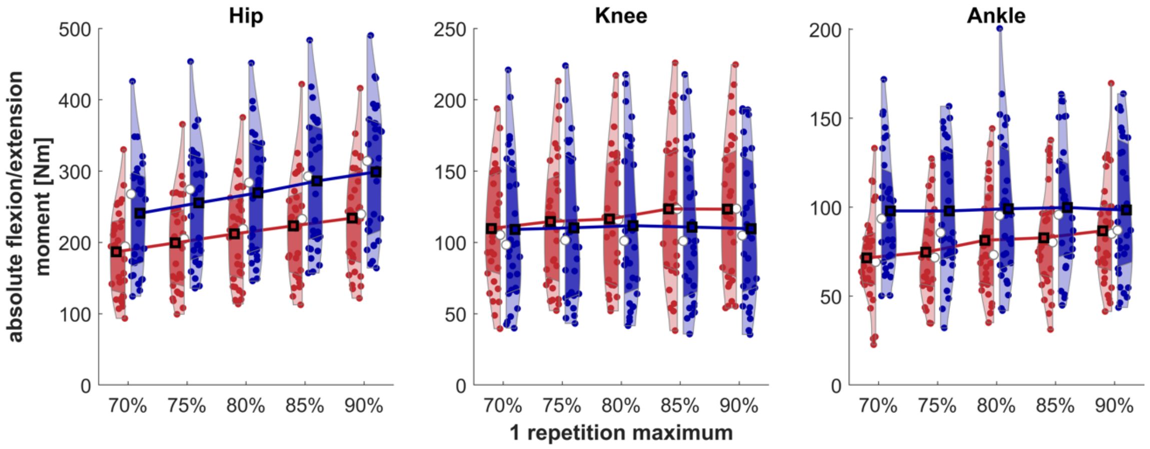

Figure 1: Absolute joint moments during squats with different intensities. Each coloured circle represents one participant; black squares represent mean values; white circles indicate median values; darker areas indicate quartiles; red is ECC, blue is CON.

In terms of the relative values, the hip flexion/extension moment was significantly higher during CON compared to ECC (5.0±0.7%; $p<0.001$, $\eta^2_p=0.614$; Figure 2). Post-hoc analyses indicated that the relative hip flexion/extension moment during CON at 70%F_{max} was significantly lower compared to every other intensity of CON (70% to 75%F_{max}: $p=0.012$, $\eta^2_p=0.412$; 70% to 80% - 90%F_{max}: $p<0.001$, $\eta^2_p=0.412$).

The relative knee flexion/extension moment was significantly different between ECC and CON (6.2±0.7%; $p<0.001$, $\eta^2_p=0.714$), with smaller CON values. Post-hoc analyses revealed that the relative knee flexion/extension moment at 70% was significantly higher than at 80%F_{max} to 90%F_{max} (70% to 80%F_{max}: $p=0.005$, $\eta^2_p=0.310$; 70% to 85% - 90%F_{max}: $p<0.001$, $\eta^2_p=0.310$).

The relative ankle plantar-/dorsiflexion moment showed a significant difference between ECC and CON (1.2±0.5%; $p=0.014$; $\eta^2_p=0.187$), with higher CON values. Post-hoc analyses indicated that when comparing intensities, a significant difference in CON was observed between 70% and 85%F_{max} ($p=0.002$, $\eta^2_p=0.203$) and 70% and 90%F_{max} ($p<0.001$, $\eta^2_p=0.203$).

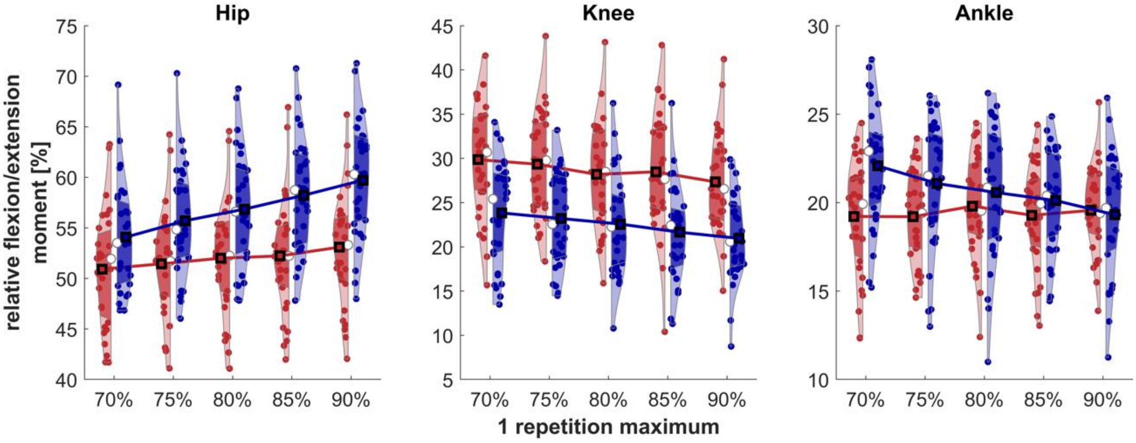

Figure 2: Relative joint moments during squats with different intensities. Each coloured circle represents one participant; black squares represent mean values; white circles indicate median values; darker areas indicate quartiles; red is ECC, blue is CON.

DISCUSSION: To the best of the authors' knowledge this is the first study that quantified absolute and relative hip, knee, and ankle joint moments during squats with increasing intensity in elite powerlifters. Against our hypothesis we observed significant different RJM with increasing loads. The relative knee joint moment decreased with an increasing load in both ECC and CON. As the ankle joint moment also decreased, at least in CON, with an increasing load (while remaining constant in ECC), which implies that the hip joint must accommodate the additional moments. This unequivocally suggests that the hip joint is the dominant load-bearing joint during the squat and becomes even more dominant with increasing loads. The results suggest a tendency toward a common compensation strategy among elite powerlifters and it appears that the knee joint and its extensor muscles are the potentially limiting factors, prompting an effort to shift the load onto the hip extensor musculature, which still has untapped potential. This phenomenon of a non-increasing relative muscle effort of the knee extensors during squats with increasing intensity has already been observed in recreationally trained women but not in elite powerlifters (Bryanton et al., 2012).

The hip joint emerged as the structure responsible for most of the total moment. Even at 70%F_{max} it accounted for 50.9±5.7% of total moment during ECC and 54.0±5.32% during CON. This proportion increased up to 53.1±5.5% (ECC) and 59.7±5.8% (CON) at 90%F_{max}. In terms of potential performance enhancement, in addition to targeted training of the knee extensors to address their relative deficit, a technique modification that allows for a more hip-dominant execution might be particularly beneficial.

The absolute moment on the knee joint during the squat remained constant between 70% and 90%F_{max} during CON. Hence, we hypothesise that the knee extensor muscles do not tolerate any further moment and are already operating near their maximum force capacity when the squat is performed with 70%F_{max}. While our study only focused on joint moments, future research should include estimates of muscular forces to validate our proposed hypothesis.

CONCLUSION: Our study showed a consistent shift in loads from the knee to the hip joint as squat intensity increased, revealing a prevalent load-distribution strategy among elite powerlifters. From this dynamic insight, three conclusions can be drawn: (a) firstly, the hip joint is likely to become the primary load-bearing joint with increasing load, thus emphasizing the importance of hip extensor muscles as the external load increases. Secondly (b), given that the knee joint moment does not increase with higher intensity, it is advisable for the squat technique to be hip-dominant (sitting back and minimizing forward knee movement). And thirdly (c), since any technical alteration during the squat, especially under high loads, poses an additional challenge for athletes, the hip-dominant technique should be ingrained and trained even at lighter loads.

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