IMPACT OF FEMORAL MORPHOLOGY ON MUSCLE FORCES AND JOINT LOADS DURING HIGH-LOAD SQUATS IN ELITE POWERLIFTERS - A PRELIMINARY INVESTIGATION

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This study investigated the effects of femoral morphology on musculoskeletal loading during high-load squats. Three Austrian top-ranked powerlifters executed competition-style squats at 90% of their 1-repetition-maximum, captured with a 3D motion capture system. Femoral anteversion (AVA) and neck-shaft angles were quantified from magnetic resonance images. For each athlete, two musculoskeletal models were created: 1) generic and 2) athlete-specific femoral geometry. Muscle forces and joint contact forces were estimated using static optimisation and normalized to bodyweight (BW). Results show increases in hip and knee muscle work (2-14 J/BW) and hip and knee joint contact forces (0.5-2.3 BW) when comparing generic with athlete-specific models, particularly in athletes with low AVA. Findings suggest that low AVA leads to increased musculoskeletal loading during high-load squats.

KEYWORDS: squatting, powerlifting, muscle forces, femoral geometry, OpenSim

INTRODUCTION: Powerlifting is a sport whereby athletes attempt to lift maximal loads through three primary lifts: squat, bench press, and deadlift. From a competitive perspective, athletes are required to complete lifts with standardised technique, however some variations are allowed which impact performance and affect musculoskeletal loading (Escamilla et al., 2001). Together, knee, hip, and thigh muscle injuries account for 47-64% of injuries in competitive powerlifting (Bengtsson et al., 2018; Strömbäck et al., 2018), with 42% of injuries having originated from squat training or competition (Strömbäck et al., 2018). Given the link between tissue loading and injury (Liu et al., 2012; Torzilli et al., 2010), understanding the interplay between athletes' squat technique, and musculoskeletal loads is paramount to further optimise training and rehabilitation programmes.
In addition to technique constrains in powerlifting, athletes are also constrained by their anthropometrics and bone geometry. Muscle paths and musculoskeletal loading both depend on bone geometry, particularly of the proximal femur (Kainz et al., 2023; Ng et al., 2019). A simulation study showed that large femoral anteversion (AVA>33º) and large neck-shaft angles (NSA>153º) lead to increased muscle co-contraction and consequently increased hip and knee joint loads during walking compared to simulations based on models with typical NSA and AVA angles (Kainz et al., 2023). Low AVA slightly decreased muscle forces and joint loads during walking (Kainz et al., 2023). However, the impact of athlete-specific femoral geometry on muscle and joint forces during competition-style heavy squats are yet to be investigated.
During our research with elite-level powerlifters, we noticed that most athletes have low AVA angles. Therefore, the aim of the present study was to evaluate the effects of femoral geometry on required muscle and joint loading during heavy-load squats (90% 1RM). We hypothesised that the low AVA seen in our powerlifting cohort would result in lower required muscle forces and lower hip and knee joint contact forces compared to a reference model with typical AVA.

METHODS: Seven elite powerlifters active members of the Austrian national powerlifting team at the time of testing, were recruited, and 3 were analysed for this study (Table 1). Participants attended one motion capture session and underwent a magnetic image resonance (MRI) scan of the lower limb. After arrival to the laboratory, participants underwent a self-paced warm-up and performed one squat at 70%, 75%, 80%, 85%, and 90% of their 1-repetion maximum (RM) following to the rules of the International Powerlifting Federation (IPF, 2024). Resting times between attempts were self-selected to ensure optimal individual preparation.

Table 1. Characteristics of the participants. BMI: body-mass index; Squat 1RM: the estimated (calculated) one-repetition maximum in the squat; WILKS score: Score that allows comparison between different weight classes; AVA: femoral anteversion angle; NSA: femoral neck-shaft angle.

	Age (years)	Gender	BMI	Years training	Squat 1RM (kg)	WILKS score	AVA (°)		NSA (°)	
							right	left	right	left
Athlete 1	**25**	**M**	**28.8**	**8**	**250**	**453.65**	**4.4***	**4.7***	**130.5**	**130.3**
Athlete 2	**26**	**M**	**25.8**	**11**	**205**	**473.75**	**2.0***	**3.5***	**132**	**129.9**
Athlete 3	30	M	29.3	10.5	280	477.51	12.7	8.3	132.2	130.9
Athlete 4	41	W	21.7	21	120	467.43	2.5*	18.7	130.9	124.9
Athlete 5	**25**	**M**	**31.2**	**9**	**280**	**484.01**	**23.1**	**28.1**	**129.1**	**130.9**
Athlete 6	25	M	28.1	5	257.5	443.05	15.2	5.7	126.3	121.7
Athlete 7	24	M	31.4	11	277.5	471.15	10.2	0.9*	135.8	134.8
Mean± Std	28.4± 5.9		28,1± 3,4	11.3± 5.0	238.6± 58.6	467.22± 14.23	10.0± 7.7	10.0± 9.8	131.0± 2.9	129.1± 4.3

* outside normal values for AVA (5° to 25°) or NSA (110° to 140°). Participants in **bold** were included in the analysis for the present abstract.

During all squat trials, ground-reaction forces from two force plates (Kistler Instruments AG, CH, 1000Hz) and trajectories of 30 lower limb markers were recorded simultaneously, using a 12-camera three-dimensional motion capture system (Vicon Motion System, Oxford, UK, 200Hz). Data was pre-processed and converted to input files using Vicon Nexus 12.0 and a freely available setup tool for MATLAB R2021a (Koller, 2022) and Python 3.8 (Goncalves, 2023).Musculoskeletal simulations were performed using OpenSim (Delp et al., 2007) and a full-body musculoskeletal model (Rajagopal et al., 2016). The model included three degrees of freedom at the hip and knee, as well as two degrees of freedom at the ankle joint. The model was adapted to prevent unphysiological moment arms for the hip and knee muscle during deep squatting positions (Catelli et al., 2019). Two models were created for each participant: (i) one based on the femoral geometry of the generic model (Catelli et al., 2019), (ii) one including the personalized femoral geometry. For the personalized model, the generic femoral geometry was modified to match the subject-specific AVA and NSA using a freely available MATLAB tool (Veerkamp et al., 2021). NSA and AVA were calculated using a common method (Sangeux & Polak, 2015). Generic NSA and AVA were quantified from the model femoral geometry (NSA = 123º, AVA = 18º) and values fall within typical values in adult populations, i.e. AVA 5° to 25° and NSA 110° to 140° (Alexander et al., 2019; Fischer et al., 2020). Subject-specific NSA and AVA were quantified from the participant's MRI images. Both, generic and personalized-femur, models were scaled to the anthropometrics of the participant using marker data recorded during a static trial (Kainz et al., 2017).
Joint angles and moments were calculated using the *Inverse Kinematics* and *Inverse Dynamics* tools in OpenSim, respectively. Muscle moment arms were verified visually and when discontinuities were observed muscle paths were adjusted to ensure physiological fibre dynamics. To ensure muscle torques could be produced by muscle actuators with minimal external actuator force, all muscles maximal isometric force was increase by a factor of 10. Muscle forces were calculated using the *Static Optimization* tool by minimizing the sum of squared muscle activations to match experimental torques. Finally, joint contact forces were calculated (Steele et al., 2012). Muscle and joint contact forces were normalized to participant's body weight (BW). Muscle work (J/BW) was calculated as the integral of muscle force-length curve and normalized to body weight. Given the preliminary nature of the presented results, comparisons were made case by case removing the need for a statistical analysis.

RESULTS: The presented results provide preliminary findings, only including athletes 1, 2, and 5 (**Error! Reference source not found.**). Participant 1 and 2 presented with normal NSA and low AVA while participant 5 presented with normal NSA and normal AVA. Compared with the generic model, personalised model showed larger hip and knee muscle work for athlete 1 (hip = 4.1 to 14.6 J/BW, knee = 6.8 to 8.2 J/BW) and athlete 2 (hip = 5.1 to 9.9 J/BW, knee = 4.4 to 11.2 J/BW), while athlete 5 only showed moderate differences (hip = -1.7 to 2.6 J/BW, knee = 1.2 to 2.4 J/BW) (Figure 1, A). Compared with generic model, personalised model showed larger hip and knee joint contact forces in athlete 1 (0.9 to 2.4 BW) and athlete 2 (0.5 to 2.4 BW) but not in athlete 5 (0.1 to 0.5 BW) (Figure 1, B). Ankle muscle work and joint contact forces were only modestly altered when comparing generic and personalised models.

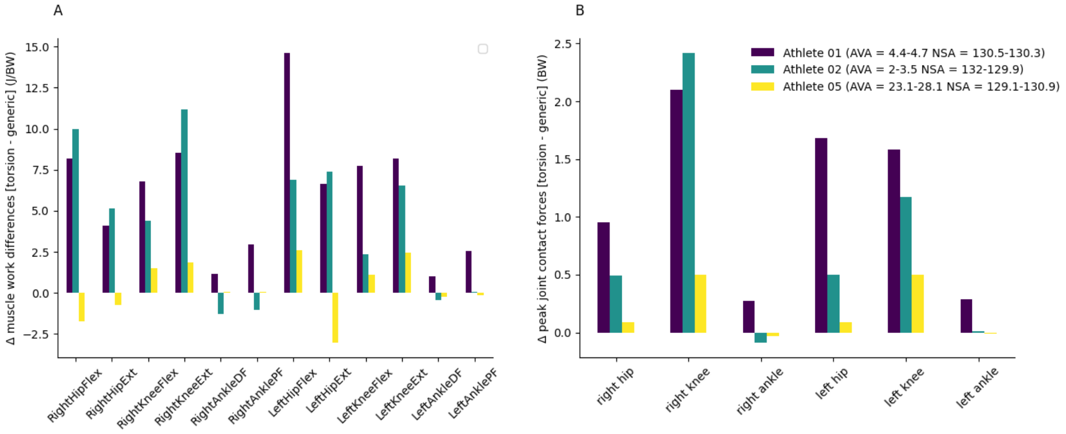

Figure 1. A. Individual differences in muscle work during heavy squats (90% 1RM) between generic models and models with personalised femoral anteversion (AVA) and neck-haft angle (NSA). Athlete 01 and 02 presented with low AVA, while Athlete 05 presented with normal AVA. Model generic values: AVA = 18º, NSA = 123º. **B.** Individual differences in peak joint contact forces during heavy squats between generic and personalised models.

DISCUSSION: The goal of this study was to evaluate the effects of low AVA seen in powerlifters, on estimates of muscle work and joint contact forces during competition-style heavy-load squats. Contrary to our hypothesis, the presented results showed that the 2 athletes with low AVA had large increases in muscle work and joint forces when comparing estimates from personalised and generic models. Thus, we suggest, based on our preliminary results, reduced AVA reduces both muscle efficiency (more work to lift the same load), and increases joint loading at hip and knee joints.

Our results are surprising considering joint contact force during walking remained unchanged when reduced AVA was simulated (Kainz et al., 2023). Joint kinematics and biomechanical demands largely differ between walking and squatting, especially with high loads (Yavuz & Erdag, 2017), which likely explains the partly surprising finding. The increases in joint forces were accompanied by increases in muscle work and potentially muscle co-contraction, which is in line with previous experimental and simulation studies (Kainz et al., 2023).

The low femoral AVA seen in most participants of our study might be caused by bone adaptations driven by heavy loading (Scorcelletti et al., 2020). The relationship between high chronic loading and decreased AVA seems to match observations of low AVA in obese people (Galbraith et al., 1987). The relative high body mass index in our athletes combined with the high bone loads during powerlift training and competitions seem to cause similar bony adaptations as seen in obese people. Our findings additionally suggest that the low AVA does not have any functional benefit for the powerlifting athletes. However, these preliminary findings remain to be confirmed with longitudinal approach and larger sample size.

CONCLUSION: Our findings showed that low femoral AVA (~4º) lead to larger muscle work and joint contact forces during heavy squatting (90% 1RM) compared with typical AVA (18º). The present results suggest that low AVA is caused by bone adaptation due to high loads but does not have any sport-related benefit for the athletes. Further analyses are still ongoing, and we aim to present the simulation results from all our participants at the ISBS conference.

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