COMPARISON OF ANGLES AND THE CORRESPONDING MOMENTS IN KNEE AND HIP DURING RESTRICTED AND UNRESTRICTED SQUATS

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The aim of this study is the comparison of angles and the corresponding moments in knee and hip during squatting. The five subjects performed restricted and unrestricted squats. The experimental set-up consisted of a motion capture system and two force plates. The loading conditions were 0, ¼ and ½ BW. The moments and the force were calculated using inverse dynamics. Overall, the maximal moments were observed in the knee during unrestricted squats and in the hip during restricted squats. Comparing the moments at a knee angle of 60º, the loading conditions have a larger influence than the type of execution. The moment in the knee is 10.4%, respectively 11.2% lower with ¼ and ½ body weight during restricted squats. In the hip, the moment is 15.5 %, respectively 14 % higher for the same conditions. The angle of the hip remains rather constant. This most likely implies a higher load to the lower back. Hence, the exercise instruction should be adapted to the aims and the training condition of the athlete.

KEY WORDS: squats, movement analysis, force, moments, exercise.

INTRODUCTION: The squat is one of the most common exercises in sport and rehabilitation. In Switzerland, squatting has one of the highest risks during training because of overload or wrong execution (Müller, 1999). Fifty percent of all injuries occuring during training concern the lower extremities or the back. Therefore, a correct execution of the squat exercise is important if not to compromise the positive effects of the training (Dunn et al., 1984, Cappozzo et al., 1985, Chandler et al., 1989, Fry et al., 2003). A widespread guideline for the barbell squat is the need to keep the knees from moving forward past the toes. To our knowledge, the instruction for squats regarding the position of the knee are based on studies of McLaughlin et al. (1977 and 1978) and Ariel (1974) and are established in Europe and in the NSCA (Fry et al., 2003).

From a biomechanical point of view it has been discussed that during the movement of the knee beyond the toes, shear forces accrue that might harm the knee (Ariel, 1974). This shear force is below the ultimate load of healthy cruciate ligaments (Andrews et al., 1983 and Woo et al., 1991). As a second argument, the pressure between the patella and the femur rises with the flexion of the knee (Escamilla, 1998, Nisell & Eckholm, 1984 and 1986). In general, this pressure seems to be within the limit of the tolerated load (Woo et al., 1991).
This study was designed to compare the angles of the knee and the hip and the corresponding moment during unrestricted (UR) and restricted (R) squats.

METHODS: Data Collection: Kinematics and kinetics of squat exercise was evaluated using a 12 camera 3D Vicon (Oxford, UK) system. The five subjects were all students of movement science with experiences in weight lifting. The average weight was 71.0 ± 12.5 kg, the age 25.4 ± 5.3 and the height 1.75 ± 0.05 m. They performed restricted and unrestricted squats with zero, ¼ bodyweight (BW) and ½ BW loading using a barbell. The barbell position was on the trapecius muscle. When performing a restricted squat, the knee is not allowed to go beyond the toes. The side view of the knee and the toes was projected onto a screen in front of the subject. The subject was able to control the position of the knee in respect to a vertical line in front of the toes. No external force was applied to the knee. For the unrestricted squat, there was no restriction on the movement of the knee. To determine the force for each foot, two Kistler force plates (Winterthur, CH) were used. The marker set consisted of 53 skin markers including 20 for the spine (Bachmann et al., 2008).

Data Analysis: Joint centers were functionally defined and the estimation of the joint rotations was based on a least-square fit of two point clouds and orthogonal anatomically defined joint coordinate systems. For the calculation of the moments, an inverse dynamics based on the position of the body and the ground reaction force was performed. In respect to the body weight of the subjects, the moments were normalized to BW.

RESULTS: The moments of the knee and hip at a knee angle of 60º and the maximal moments are given in Table 1 and 2. As expected, the maximal moments during restricted squats are lower in the knee and higher in the hip (Table 3). At a knee flexion of 60^{o}, the moment in the knee is the same with no extra load, 10.4 % smaller with ¼ BW load, and 11.2 % smaller with ½ BW for the restricted squat (Figure 1). In the hip, the maximal moment is 6.3 % and 6 % higher for restricted squats (Figure 2). Looking at a knee angle of 60º, corresponding to a similar condition for the length of the muscle, the moment is just 10% smaller with the restricted squats, whereas the moment in the hip is 15.5 %, respectively 14.0 % higher for ¼ and ½ BW extra load. When comparing the results of this work, the values are in good agreement with Fry et al. (2003) except for the maximal moment of the hip.

Table 1 Average moments of the knee and hip at a knee angle of 60 º normalized to the body weight [Nm/Kg]

Load BW	M_{KNEE} UR(60º)	M_{KNEE} R(60º)	M_{HIP} UR(60º)	M_{HIP} R(60º)
0	0.60±0.09	0.61±0.07	0.30±0.06	0.31±0.04
¼	0.69±0.11	0.63±0.07	0.49±0.09	0.58±0.06
½	0.79±0.15	0.71±0.13	0.74±0.11	0.86±0.12

Table 2. Average maximum moments of the knee and hip [Nm]

Load BW	$MaxM_{KNEE}$ UR	$MaxM_{KNEE}$ R	$MaxM_{HIP}$ UR	$MaxM_{HIP}$ R
0	61.5±9.3	57.9±7.9	47.2±5.7	47.2±5.7
¼	78.7±10	66.5±5.7	73.6±7.0	78.7±4.3
½	93.7±12	77.9±10.7	100±13	106.5±8.6
1*	150.1±50.8	117.3±34.2	28.2±65.0	302.7±71.2

* Fry et al. (2003)

Table 3. Comparison between unrestricted and restricted squats (unrestricted is equal to 100 %).

Load BW	M_{KNEE} 60º	M_{HIP} 60º	Max Knee angle	Max Hip angle	$MaxM_{KNEE}$	$MaxM_{HIP}$
0	0%	3.2%	-11.1%	1.4%	-5.8%	0
¼	-8.7%	15.5%	-14.0%	1.8%	-15.5%	6.3%
½	-10.1%	14.0%	-12.0%	2.7%	-16.8%	6%
1*			-6.9%	5.1%	-28.0%	Factor 10 higher

* Fry et al. (2003)

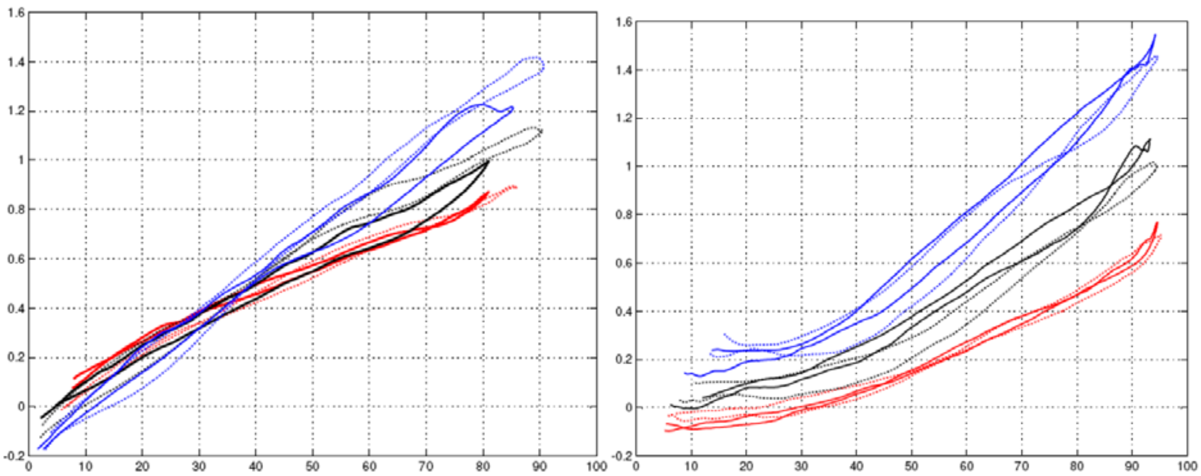

Figure 1: left: Knee flexions [º] vs. moments [Nm/Kg], red 0 BW load, black ¼ BW load, blue ½ BW load, line for restricted (R) and dots for unrestricted (UR) squats. Right: Hip flexions [º] vs. moments [Nm/Kg].

DISCUSSION: The squat is mainly an exercise for the quadriceps. Hence a certain moment in the knee is needed to set a stimulus. The restriction of the position of the knee implies either a shift of the center of pressure (COP) toward the heel or a compensation mechanism of the upper body. Shifting the COP towards the heel reduces the stability of the stands. Especially with high weights a stable stand is required.

The compensation mechanism leads to higher moments in the hip. One of this compensation mechanism is the bending forward of the trunk during restricted squatting. Assuming a simple kinematic chain model, the higher moments in the hip are leading to a higher load to the lower spine.

Performing unrestricted squats results in higher maximal moments in the knee and lower moments in the hip. Whereas the angle of the knee is higher for unrestricted squatting, in the hip, the flexion angle is similar in both conditions. Therefore compensation mechanisms such as flexion of the spine are expected to counteract these differences.

The higher maximal moment in the knee during unrestricted squatting can be explained by the higher angle of the knee. This shows the importance of choosing the proper depth of the squat.

A rise in the torque for the hip by a factor of 10 between un- and restricted squats as given by Fry et al. (2003) was not observed and seems rather unlikely given the changes of the angles in the knee and the hip.

Of course great care must be taken on the depth of the squat not only the moment of the knee rise, but the stress on the hip and the lower back too.

CONCLUSION: In this study the angles and the corresponding moments of the knee and the hip were determined. Not surprisingly, the moment in the knee rises with the angle and the load. Even though the maximum moment is higher in the knee, the unrestricted squat has comparable moments at the same angle of the knee. The stress on the hip and most likely on the lower back, is lower during an unrestricted squat. For these reasons, the unrestricted squat may be the right choice for most athletes.

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