The squatting exercise, performing a knee bend while carrying a weight on the shoulders, is an often used and important method for hip, knee, and back muscle training (3,18,22,23). Many athletes in different disciplines use this type of exercise as the basic exercise to strengthen the leg muscles, and the method is considered supreme for this purpose by many coaches (4,29). Weightlifters and powerlifters use squatting as one of the most important parts of their training programs, and for the powerlifters this kind of squatting is directly included during their competition performance (13,14,15). In the weightlifting competition the back squat is not directly included, rather the front-squat with the barbell on the chest; still the back-squat training is important also for the weightlifters.

The squatting exercise can be performed in different ways. The weights on the shoulders and numbers of repetitions can vary depending on the purpose. Squatting depth is another important factor and the parallel and deep squat dominates. During the parallel squat, the knees are flexed until the posterior borders of the hamstrings muscles are parallel to the floor, whereas during the deep squat the knees are maximally flexed. In a previous study (32), we showed that the quadriceps muscle activity is the same for these two different types
of squats but that the load on the knee joints is larger for the deep squat.

There are two main techniques for the squatting exercise with the bar on the back; the “high-bar” squat and the “low-bar” squat (29). The names of the techniques are related to the placement of the bar on the back. The bar is either centered across the shoulders just below the spinous process of the C7 vertebra, “high-bar,” or further down on the back across the spine of the scapula, “low-bar.” It has been shown that the low-bar squat is characterized by more forward lean of the trunk (12) and that powerlifters use the low-bar squatting technique since this enables them to lift heavier loads (29). The weightlifters mainly use the high-bar technique, which more simulates the movement during their snatch and clean and jerk competition. During competition the weightlifters use the front-squat movement, which is done in an upright position since they cannot balance the weight with too much forward lean of the trunk. Athletes other than lifters may use techniques that are not strictly defined.

It is known that injury may occur by overloading the knee joint (1) and also that squatting generates high forces which can result in serious injuries (16, 28). During the jerk dip in weightlifting competition, with its large acceleration, serious injuries also have occurred (33). Whether there is a difference in loading moments of force on the hip and knee between the high- and low-bar squat is, however, not known, but this is of interest, e.g., when planning the training after an injury. In this study we analyze how high- and low-bar squats effect hip and knee load and the thigh muscle activity. Studies such as this offer one way of improving our knowledge of the biomechanical effects of different training methods.

METHOD

Subjects

Eight weightlifters and six powerlifters, all of Swedish national class in their age and bodyweight categories, participated in the study. Written informed consent was obtained from the subjects. The mean age of the weightlifters was 19 yr (SD ± 3) and their mean weight was 82 kg (SD ± 11). The mean age of the powerlifters was 31 yr (SD ± 3) and their mean weight was 87 kg (SD ± 20) (Table 1). One of the weightlifters had pain in the knees due to previous overstrain, but he felt it did not affect the way he performed the squat with the moderate weights used in this study. All other lifters were without dysfunction in the locomotor system.

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TABLE 1. Subject data; 1 RM is the subject’s one-repetition maximum for the deep squat.

Procedure

The weightlifters performed high-bar squats and the powerlifters performed low-bar squats. We did not let all lifters do both high- and low-bar squats since by testing some of the lifters we realized that they could not perform the type of squat they were not used to in an optimal way. Two different types of squatting depths were also studied, the parallel squat and the deep squat. During the parallel squat, the knees were flexed until the posterior borders of the hamstrings muscles were parallel to the floor, and during the deep squat the knees were maximally flexed. Before starting the parallel squat, the appropriate squatting depth was indicated with a non-weight-bearing stop bar beneath the subject’s buttocks. During the
indicated with a non-weight-bearing stop bar beneath the subject's buttocks. During the movement, the subjects flexed their knees until contact was made with the bar. All movements were performed on a force plate (60 × 30 cm), where the feet were placed symmetrically. They could freely choose their stance with, and no subject felt restricted by the 60-cm width of the force plate. The bar weight was individually based on the subjects' all time one-repetition maximum (1 RM) for a deep squat exercise, as reported by the subjects. A weight of 65% of the 1 RM was chosen. None of the lifters wore wraps or belts since this could have effects on the calculation of the moment of force and since it has been shown that belts can decrease the electromyographic activity during squatting. One of the weightlifters performing a deep squat is shown in Figure 1.

For motion analyses a video camera (Panasonic MS1, frame rate 25 Hz, with high speed shutter 1/1000) and a video recorder (Panasonic 8500) were used. The camera was placed to the left of all subjects at a focal distance of 8 m. For synchronization of the force recordings and the video, the computer was triggered by an optical time indication panel visible on the video recording. Skin markers were placed at five places on the body: trunk (mid-axillar line at umbilicus height), hip (superior part of greater trochanter), knee (lateral epicondyle), ankle (lateral malleolus), and foot (head of fifth metatarsal). The coordinates for these markers were extracted frame-by-frame from the video recordings with a video position analyzer (FOR-A company, VPA 1000).

The ground reaction forces on the feet were measured with a Kistler multi-component piezoelectric platform (type 9281 B), which measured the vertical, anteroposterior, and...
Piezoelectric platform (type 9281 B), which measured the vertical, anteroposterior, and lateral ground reaction forces during rising. All force signals (sampled at 100 Hz) were channelled through Kistler amplifying units (type 5006) to a microcomputer (Luxor ABC 800) where they were A/D converted and stored. The position of the center of pressure of the reaction force between the feet and the ground was also obtained from the force plate. Combining these data with the video coordinates gave the appropriate sagittal moment arms with respect to the hip and knee joint markers. Dempster's anthropometrical data (6) were used to determine the segmental masses and their mass center locations.

A computer program based on free-body mechanics was designed to calculate the moments of force about the hip (superior part of greater trochanter) and knee (center of lateral epicondyle) by multiplying each external force (body segment weight or horizontal or vertical reaction force) by its moment arm length (Fig. 2). A “semidynamic” method was used, which incorporated ground reaction forces measured from a force plate and gravitational contributions from body segments. Semidynamic methods have proved to give results very close to calculation with fully dynamic methods (21). McLaughlin et al. (23) and Lander et al. (19) have also analyzed torques and joint forces for squat movements with both dynamic and semidynamic methods, and they found only minor differences, indicating that this kind of method is adequate for these calculations. These studies show that the inertial forces are low compared with the ground reaction forces. Similar methods for calculation of moment of force have been used earlier (5,9,26) and this particular system has been used in several investigations (e.g., 31). The same type of technique has also been used in similar weightlifting studies (2,10), but fully dynamic methods also are used in weightlifting studies (11). The patellofemoral compressive force during the parallel squat was calculated using our moment of force data and diagrams previously published by Nisell and Ekholm (27).

![Figure 2-Calculation of the moment of force about the hip (MH). RX and RY are the horizontal and vertical components of the reaction force from the force plate. WT, WS, and WF are the segmental weights of thigh, shank, and foot. (XH, YH) are the X and Y coordinates for the marker on the hip joint. (XT, YT), (XS, YS), and (XF, YF) are the X and Y coordinates for the center of gravity of the thigh, shank, and foot. XR and YR are the X and Y coordinates of the application point of the reaction force.]

\[ M_H = W_T(X_{Hx} - X_T) + W_S(X_{Shx} - X_S) + W_F(X_{Fhx} - X_F) + R_X(Y_{Hx} - Y_R) + R_Y(X_{Hx} - X_R) \]

The activity in the vastus lateralis, rectus femoris, and the long head of the biceps femoris muscles was recorded (Devices M4, AC8) by means of full-wave rectified low-pass-filtered and time-averaged electromyogram (linear envelope EMG). The low-pass time constant was 100 ms. Surface (Ag/AgCl) electrodes were placed on the skin over the muscles in the fibers direction, with an inter-electrode distance of 2 cm. For control of artifacts, direct EMG was visualized in parallel on an oscilloscope (Tektronix RM565).
To quantify the muscular activity and to compare the activity between different squats, the EMG activity during the movements was related to a static reference action. As reference contraction, a parallel squat with a barbell weight of 65% of 1 RM was chosen. The peak EMG value during a 3-s static parallel position was used as the reference value. The muscular activity is expressed as a quotient of the reference value. Normalization like this has been used earlier (7,8,17).

Statistics

Since the data were approximately normally distributed, and since this type of data in general is known to be normally distributed, the parametric test was used for the statistical analysis. Comparison was done between parallel and deep squats within each group, and between powerlifters and weightlifters for the parallel and deep squat, respectively. For the comparison between weightlifters and powerlifters, one has to be aware of the differences in groups concerning body weights and lifted weights.

RESULTS

Moments of Force

The joint moment of force curves for one weightlifter and one powerlifter are shown in Figure 3. All flexing loading moments of force are expressed as positive, which means that the curves describe mainly flexing loading moments for both the hip and the knee. These flexing moments are counteracted by the extensor muscles producing extending moments on the hip and knee joints. The calculated moments are the net muscular moments: the effects of antagonistic muscular activity are not considered. The distinct peaks on the curves correspond to the turning point during the change from knee flexion to knee extension. The two lifters have different load distributions. The powerlifter put relatively more load on the hip joint than on the knee joint while the weightlifter had a more equal distribution of load between hip and knee.
Figure 3—Individual moment curves for one weightlifter and one powerlifter performing a deep squat. Flexing loading moment of force are expressed as positive.

Figure 4 shows the mean maximum moments of force for the hip and knee joints for the different lifters during both the parallel squat and the deep squat. Also the mean moment data show that the weightlifters have a more equal load distribution between hip and knee than the powerlifters. The mean maximum moment at the hip joint was for the powerlifters 324 Nm (deep) and 309 Nm (parallel). The corresponding values for the weightlifters were 230 Nm (deep) and 216 Nm (parallel). The powerlifters had a significantly higher hip moment of force both for the parallel and deep squat ($P < 0.05$). The differences between the parallel and the deep squats within each group were not significant. At the knee joint there was a different situation. Although the powerlifters were heavier and lifted heavier loads than the weightlifters, they showed the lowest moment of force both for the parallel and the deep squats, and the difference was significant ($P < 0.05$) for the parallel squat. The mean maximum moments were for the powerlifters 139 Nm (deep), and 92 Nm (parallel). For the weightlifters the mean maximum flexing knee moments were 191 Nm (deep) and 131 Nm (parallel). Independent of technique, the load on the knees increased significantly with increasing squatting depth ($P < 0.005$).
The weightlifters showed positive correlation between hip load and the total mass of lifter and barbell. The strongest correlation was found for the deep squat \( r = 0.92 \), but the correlation was also significant for the parallel squat \( r = 0.88, P < 0.01 \). There was also a tendency to positive correlation between hip load and total mass for the powerlifters both for the parallel \( r = 0.75 \) and the deep \( r = 0.76 \) squat, but with only six lifters the correlation was not significant. The corresponding values for the knee joint showed that the moments of force did not increase proportionally with external load. This has been found earlier for world class weightlifters (2).

**Knee Forces**

We thought it would be interesting to calculate one force component in the knee that would reflect the magnitudes of the forces in the knee during squatting. Therefore, the patello-femoral compression force for the parallel squat was calculated. The mean peak compression force for the weightlifters was 4700 N (SD ± 590) and for the powerlifters 3300 N (SD ± 1700) (26).

**Electromyography**

The muscular activity in the vastus lateralis, the rectus femoris and the biceps femoris muscles was recorded and the mean muscular activity peaks, with 95% confidence intervals, are shown in Figure 5. For all muscles and both the parallel and the deep squat the mean peak muscular activity was higher for the powerlifters. However, in this study with six powerlifters and eight weightlifters, a significant difference was found only for the rectus femoris muscle \( P < 0.05 \). The highest activity levels both for the weightlifters and the powerlifters were found for the biceps femoris muscle, with a relative muscular activity of about three times the reference level. However, the activity in this muscle also showed the greatest individual difference.
Movement and Joint Angles

The knee flexion angles were slightly smaller for the powerlifters. The mean knee flexion angle for the powerlifters were 111° (SD ± 5) for the parallel and 126° (SD ± 4) for the deep squat. The corresponding angles for the weightlifters was 116° (SD ± 5) for the parallel and 138° (SD ± 3) for the deep squat. Analyses of the hip flexion angles show that both the weightlifters and the powerlifters increased these angles with increasing squating depth. The mean maximal hip flexion angles for the weightlifters was 111° (SD ± 8) during the parallel squat and 125° (SD ± 4) during the deep squat. The corresponding angles for the power lifters were 132° (SD ± 4) and 146° (SD ± 3), respectively. By flexing the hip more, the powerlifters leaned the trunk farther forward (Fig. 6).
**DISCUSSION**

Since squatting exercise is an important part of the strength training for many athletes, it is important to understand the effects of different squatting techniques. In this study we used weightlifters and powerlifters to demonstrate effects of the high- and low-bar squats. We are aware that there is a difference in age between the two lifter categories, but the analysis showed no difference in principle muscular activity or load between the oldest and youngest lifters in each group.

The study shows the differences between the high- and low-bar techniques and also the effects on the hip and knee moment of force. The low-bar squat with the barbell further down on the back is characterized of a larger hip flexion (Fig. 6), and this technique creates a hip moment of force that in Newton-meter is almost twice as large as the knee moment. The high-bar squat, however, is performed more upright and the joint moment of force are more equally distributed between the hip and knee joints. The hip and knee angles in the present study correlate well with the angles found by Fry et al. (12) and confirm the more upright position during the high-bar squat. Although the powerlifters were larger and lifted heavier loads than the weightlifters, the mean moment of force on the knee joint was lower than for the weightlifter, and the difference was significant for the parallel squat. The powerlifters, however, had significantly a higher load on the hip joint compared with the weightlifters. The difference in hip load could be an effect of heavier lifters lifting heavier loads in addition to an effect of different technique, but the difference in knee moment of force could hardly be explained from anything else but different lifting technique. It is clear that weightlifter coaches want the squat to be done as upright as possible. This is the only way to approach the movement during weightlifting competition. Powerlifting coaches, however, want lifters to lift as much as possible with hip and back since, by experience, they know that this enables the lifter to lift heavier loads. The calculated moment of force on the joint is dependent on the size of the ground reaction force and the distance between this force and the joint center, the moment arm. By increasing hip flexion, the powerlifters manage to balance the weight closer to the knee and thereby reduce the moment arm. The moment arm between the ground reaction force and the hip joint, however, will increase, creating a higher moment of force on this joint. The high-bar squat is performed in a more balanced way where both the barbell and the trunk center of gravity are centered between hip and knee, and thereby the moments of force are more equally distributed.

The powerlifters showed higher EMG activity than the weightlifters for all investigated muscles, although the difference was significant only for the rectus femoris. The powerlifters were heavier and lifted heavier loads, but this could be the explanation to the higher muscular activity. EMG activity, however, was normalized in relation to a reference contraction with the same relative external load, which might indicate that the low-bar squat actually is advantageous from a muscular recruitment point of view. It is clear, however, that weightlifters must train with a technique close to the competition situation, which means the high-bar squat. Some other athletes might benefit from using a technique close to the low-bar squat, providing that they have the low back strength to safely perform a low bar squat.

It is a little surprising that powerlifters performing low-bar squats, with relatively low moment of force at the knee joints, have a knee extensor muscular activity even slightly higher than weightlifters performing high-bar squats with higher knee moments. The explanation must be that the moments calculated are net loading moments of force, which means that muscular co-contraction is not included in the values calculated. The activity in the biceps femoris muscle is slightly higher for the low-bar squat. The activity in the
gastrocnemius muscle and the soleus muscle was not recorded. However, since the low-bar squat is performed with the total center of gravity further forward, the need for compensatory ankle plantar flexion will increase, which means increased activity in both the gastrocnemius and the soleus muscles. During the low-bar squat, knee flexor muscle activity increases, and hereby knee extensor co-contraction. This can explain why the knee extensor activity is high despite the relatively low net knee loading moment. As previously mentioned, one should be aware that the calculated moments are net moments of force and that the effect of co-contracting antagonistic muscles are not taken into account. A antagonistic moment of force created by the antagonist would increase the moment of force produced by the agonists. Therefore, the moment calculated in this study must be taken as minimum loading moments for the agonists. Two joint muscles can in this way serve as agonist at one of the joints and antagonists at an other. The biceps femoris for example produce an extending moment of force at the hip, but an antagonistic flexing moment of force at the knee. The magnitude of this antagonistic moment is not possible to calculate in a study like this.

Although hip extensor activity was not analyzed, it seems logical that the low-bar squat should be the best technique concerning hip extensor training since this technique create the greatest moments of force at the joint.

The patello-femoral compression force was calculated to give an apprehension of the force magnitudes. Forces in the hip and knee depend not only on the moment of force, but also on joint angle (22,24,25). For a constant moment of force joint compression forces increase with increasing flexion angle. This has been investigated for hip flexion up to 90˚ and for knee flexion up to 120˚. For the knee the patello-femoral compression force levels away between 90 and 120˚. So the reason for larger compression force in the knee for the weightlifters was not because of a larger knee flexion angles, rather related to the larger moment of force.

Both the weightlifters and powerlifters have a strict and precise squatting technique. It is probable that many other athletes in other disciplines use techniques in between the high- and low-bar techniques and that their coaches are not aware of the effects of the different techniques. Athletes should benefit from studying lifters and their technique and the different effects that can be achieved. It is known that squatting exercise is a good method for knee rehabilitation training (30), and we suggest that after a hip injury, high-bar squat should be used at the beginning to minimize the risk of hip overload. After a knee injury a squatting technique more similar to the low-bar technique should be preferred. Further investigation on, for example, shear and compression forces on the lumbar spine during the two different types of squatting technique must be important to prevent reinjury of the lower back during rehabilitation exercise.

REFERENCES


