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LOWER EXTREMITIES JOINT ANGLES DURING SQUATS – UNDEREXPLORED PARAMETER OF STANDARD REHABILITATION AND SPORTS EXERCISE

Viktor Kotiuk[A, B, D, E]

Department of Sports and Ballet Trauma of State Institute of Traumatology and Orthopedics of NAMS of Ukraine, Kyiv, Ukraine
Carolina Medical Center, Warsaw, Poland
ORCID: 0000-0001-8837-8603 | e-mail: kotyuk_v@ukr.net

Oleksandr Kostrub[A, D]

Department of Sports and Ballet Trauma of State Institute of Traumatology and Orthopedics of NAMS of Ukraine, Kyiv, Ukraine
ORCID: 0000-0001-7925-9362

Roman Blonskyi[A, D]

Department of Sports and Ballet Trauma of State Institute of Traumatology and Orthopedics of NAMS of Ukraine, Kyiv, Ukraine
ORCID: 0000-0003-2310-6345

Lyudmyla Sushchenko[B, C]

Department of Physical Therapy of National Pedagogical Dragomanov University, Kyiv, Ukraine
ORCID: 0000-0002-2461-3739

Dmitry Smirnov[B, E]

Department of Sports and Ballet Trauma of State Institute of Traumatology and Orthopedics of NAMS of Ukraine, Kyiv, Ukraine
ORCID: 0000-0003-1048-569X

Nazar Vadzyuk[B, C]

Department of Sports and Ballet Trauma of State Institute of Traumatology and Orthopedics of NAMS of Ukraine, Kyiv, Ukraine
ORCID: 0000-0002-3398-1285

[A] Study Design; [B] Data Collection; [C] Statistical Analysis; [D] Manuscript Preparation; [E] Founds Collection

Abstract The purpose was to specify the lower extremity joint angles in different squats for the future development of adequate computational models of the joints.
Methods. We investigated joint angles in the lower extremity joints in 103 athletes in different types of squats with and without added weight (barbell) 75% of 1 repetition maximum.
Results. The mean knee and hip flexion and ankle dorsiflexion angles in horizontal squats are respectively 113.42°, 128.21°, and 23.27°; in half-squats 70.60°, 87.94°, and 15.60°; in lunges 98.04°, 96.36°, and 8.02°; in Smith machine squats 94.42°, 106.28°,

and 4.46°. In a horizontal squat with a barbell, the knee joint flexion and the ankle joint dorsiflexion angles are significantly larger (by 4.56° and 3.11°, respectively) than in squats without added weight. The knee joint flexion and ankle dorsiflexion angles in lunges are significantly less in barbell squats (by 4.15° and 4.37°, respectively). The knee flexion angle in horizontal barbell squats in male athletes is significantly larger than in female athletes (by 4.71°).
Conclusions. The mean knee and hip flexion and ankle dorsiflexion angles in different types of squats are established and may be used for further research. Horizontal squats produce greater lower extremity joint angles.

Key words squats, joint angles, half-squats, Smith machine squats, lunges

Introduction

Squats are an essential exercise in the training process in many sports and a competitive exercise in powerlifting. Horizontal squats are the standard of its performance (during the competition, you need to sit at least a little below the horizontal level) (United States Powerlifting Association, 2016). Despite this, there are almost no studies of the average angles in athletes' knee, ankle, and hip joints during this exercise. There are specific standards and guidelines for squat technique (United States Powerlifting Association, 2016). However, depending on the sport, experience, the aim of performing squats, and anthropometric measures of athletes, even the same type of squat can be performed in different ways by different athletes (Lorenzetti et al., 2018; Myer et al., 2014), and the angles in the knee, hip, and ankle joints will differ significantly. Athletes who are well acquainted with the correct squat technique and have mastered it before injury or surgery, of course, will be better able to follow the instructions of a rehabilitation therapist, physical therapist, or kinesiotherapy specialist. So we must choose their technique, and hence the joint angles, as a standard. However, even among athletes, the technique of squats differs significantly while remaining within the recommended limits.

Studies that we have found either do not indicate squat depth and methods of calculating joint angles (85–106° (Lorenzetti et al., 2012)) or study deep squat (full squat) with maximum flexion in the knee joints (104.8–121.5° (McKean, Burkett, 2012), 119.0–124.8° (Zawadka, Smolka, Skublewska-Paszkowska, Lukasik, Gawda, 2020), 124.3–125.2° (Endo, Miura, Sakamoto, 2020)) which may be dangerous even for healthy athletes and even more so for patients with injuries and diseases of the joints (Escamilla, 2001; Li, Adrien, Baker, Mei, Gu, 2021). Besides this, among the described studies one investigated only 9 (Endo et al., 2020), the other 60 volunteers (Zawadka et al., 2020), but all of them were neither professional athletes nor specially trained in squatting. A critical study by Fry et al. was performed on only seven volunteers and studied only horizontal squats with the weight bar (Fry, Smith, Schilling, 2003). The most informative in this regard was the study of powerlifters and weightlifters conducted by Wretenberg, Feng, Arborelius back in 1996. Scientists have determined that the average knee joint angle during squatting to the horizontal (most likely using the neutral-zero method) in powerlifters was 111° ±5° and in weightlifters 116° ±5°. In a deep squat, these angles were 126° ±4° and 138° ±3°, respectively (Wretenberg et al., 1996). However, the study was performed on only 14 athletes and did not evaluate the forward tilt angle of the tibia, which is essential for the proper development of a computational model (especially one that takes into account the angle of the tibia plateau slope) and for tensile load test with a direct stress machine in different squats.

Squats in various modifications are widely used during rehabilitation and physical therapy for numerous injuries and diseases of the joints and after joint surgery. The matters of current interest are the following. How and what squat techniques affect specific anatomical structures of the joints? What squat modifications, at what time after injury or surgery, and with what load can we safely utilize? These issues are especially relevant for the rehabilitation of patients after reconstructive joint surgery, such as anterior cruciate ligament reconstruction. We must have a clear idea of what loads await the patient during squats. In this regard, we must understand, among other factors, the lower extremities joint angles during squats for further load calculations. Today, computer-generated simulations of joint stresses in various exercises and tensile load tests with a direct stress machine are beneficial in choosing the safest exercises and modifying their techniques to maximize the safety of their use in the rehabilitation of injuries and diseases of the joints. We need to know the average joint angles in each type of squat and the range of their oscillations between athletes/patients, as well as the angle of the tibia forward tilt to develop an adequate computational model of the knee joint for stress analysis in the anatomical elements of the knee joint (including the anterior cruciate ligament) using the finite element method and for tensile load test with a direct stress machine. We encountered the absence of these data in the scientific literature. This prompted us to conduct independent research.

The purpose of the study was to specify the lower extremity joint angles in different types of squats and the range of their oscillations for further development of an adequate computational model of the joint for stress analysis in its anatomical elements using the finite element method and for tensile load test with a direct stress machine.

Material and methods

We investigated joint angles in the knees, ankles (anterior tibial deviation angle between the floor and the shin axis), and hip joints in horizontal squats, half-squats, Smith machine squats, and lunges in 103 athletes (47 male and 56 female) engaged in weightlifting, powerlifting, bodybuilding or CrossFit with athletic titles and categories in strength sports or experience of regular strength training and squats at least 3 three times a week for at least ten years. Athletes were studied in different gyms to eliminate the subjectivity of one coach's recommendations.

There is some controversy in terminology regarding quarter squats, semi-squats, half-squats, full, parallel, and deep squats. Semi-squats are sometimes called quarter squats, and Escamilla calls semi-squat the squat to the horizontal (Escamilla, 2001). We will adhere to the more traditional terminology, where horizontal squats are the squats to the horizontal position of the thighs, and semi-squats (or half-squats) are the squats where the thighs are angled at 45 degrees to the horizontal.

After the warm-up, athletes who are well-versed in the squat technique were given the instructions to perform a horizontal squat, half-squat, Smith machine squat, and lunge with the best technique. The hip, knee, and ankle angles were measured with the neutral-zero method. The ankle angle (dorsal flexion) was measured as the tibial shaft forward tilt angle. The athlete was allowed to utilize the squatting technique he would use to fulfill the medical prescriptions regarding rehabilitation. Most athletes used mirrors in the gym for squat performance self-control. On the other hand, some of the athletes squatted without a mirror as they had used to such a technique. All the athletes were free of injuries and joint diseases that could interfere with the proper squatting technique. The added weight of 75% of 1 repetition maximum was used only by the athletes who knew their one-repetition maximum with the ideal squatting technique and were familiar with such a weight at workouts. Not all the professional athletes that utilize squats at their training sessions perform these with the maximal weight and know their one-repetition maximum.

Horizontal squats were studied in 103 athletes (47 male and 56 female), Smith machine squats were studied in 57 athletes (31 male and 26 female), half-squats – in 48 (20 male and 28 female), lunges – in 45 (20 male and

25 female). Fewer athletes were investigated performing half-squats, Smith machine squats, and lunges due to later decisions about including these exercises in the research and due to fewer athletes who routinely use these exercises in the training process and feel up to perform these exercises at a high level with ideal technique. We also studied the above-mentioned angles in the joints of the lower extremities, both among all surveyed athletes and separately for men and women and separately for squats without the extra weight and with added weight (barbell) 75% of 1 repetition maximum. Smith machine squats were performed with a 20 kg weight bar, which was an integral part of the machine. Because only a small number of athletes knew their one-repetition maximum in the Smith machine, barbell squats in the Smith machine were not studied separately.

Squats were performed with the feet approximately shoulder-width apart. In the case of squats with added weight (barbell), its weight bar was placed high on the back – on the trapezius muscle.

Results

We determined that the knee (flexion), hip (flexion), and ankle (dorsiflexion) angles in athletes of strength sports in horizontal squats are respectively 113.42° ±7.20°, 128.21° ±9.35°, and 23.27° ±6.23°; in half-squats 70.60° ±17.44°, 87.94° ±17.80° and 15.60° ±6.61°; in lunges 98.04° ±5.82°, 96.36° ±7.28° and 8.02° ±5.94°; in Smith machine squats 94.42° ±4.78°, 106.28° ±9.14° and 4.46° ±4.80°. The specified mean angles (and their standard deviations), ranges of the hip, knee, and ankle angles in different squats, separately for squats with and without added weight (barbell), for male and female athletes, are listed in Table 1 and schematically shown in Figure 1. Table 2 presents the difference and the significance of the difference in these angles in different squats between male and female athletes, between squats with and without added weight.

Table 1. The mean hip, knee, and ankle angles in different squats, their standard deviations, and ranges

The subgroup of athletes and their number	The knee joint flexion angle	The hip joint flexion angle	The ankle joint dorsiflexion or extension angle (same as tibial shaft forward tilt angle)
1	2	3	4
Horizontal squats			
All athletes 103	113,42° ±7,20° (95–132°)	128,21° ±9,35° (105–150°)	23,27° ±6,23° (11–37°)
Male athletes 47	114,64° ±6,07° (100–127°)	129,96° ±9,03° (109–150°)	24,49° ±6,12° (11–35°)
Female athletes 56	112,39° ±7,94° (95–132°)	126,75° ±9,44° (105–147°)	22,25° ±6,20° (11–37°)
All athletes without a barbell 52	111,19° ±7,47° (95–127°)	128,37° ±8,95° (110–148°)	21,73° ±6,10° (11–37°)
Male athletes without a barbell 22	113,91° ±6,45° (100–127°)	129,59° ±9,43° (110–148°)	23,23° ±5,98° (11–34°)
Female athletes without a barbell 30	109,20° ±7,64° (95–127°)	127,47° ±8,62° (115–147°)	20,63° ±6,06° (11–37°)
All athletes with a barbell 51	115,69° ±6,20° (103–132°)	128,06° ±9,83° (105–150°)	24,84° ±6,02° (11–35)
Male athletes with a barbell 25	115,28° ±5,77° (105–126°)	130,28° ±8,84° (109–150°)	25,60° ±6,15° (15–35°)
Female athletes with a barbell 26	116,08° ±6,67° (103–132°)	125,92° ±10,42° (105–145°)	24,12° ±5,93° (11–30°)

1	2	3	4
Half-squats			
All athletes 48	70,60° ±17,44° (47–114°)	87,94° ±17,80° (40–120°)	15,60° ±6,61° (3–26°)
Male athletes 20	67,30° ±14,92° (47–111°)	91,20° ±17,12° (40–120°)	13,70° ±6,33° (3–24°)
Female athletes 28	72,96° ±18,94° (47–114°)	85,61° ±18,22° (57–120°)	16,96° ±6,57° (7–26°)
All athletes without a barbell 38	63,17° ± 13,16° (47–80°)	90,92° ±18,79° (40–117°)	10,00° ±4,59° (3–16°)
All athletes with a barbell 10	73,50° ±16,11° (60–111°)	91,63° ±15,50° (71–120°)	19,25° ±4,13° (13–24°)
Lunges			
All athletes 45	98,04° ±5,82° (90–110°)	96,36° ±7,28° (90–116°)	8,02° ±5,94° (0–21°)
Male athletes 20	99,05° ±5,25° (90–108°)	97,35° ±6,77° (90–116°)	8,9° ±5,18° (0–18°)
Female athletes 25	97,24° ±6,22° (90–110°)	95,56° ±7,71° (90–113°)	7,32° ±6,50° (0–21°)
All athletes without a barbell 34	99,06° ±5,82° (90–110°)	95,41° ±6,60° (90–113°)	9,09° ±6,00° (0–21°)
All athletes with a barbell 11	94,91° ±4,78° (90–102°)	99,27° ±8,80° (90–116°)	4,72° ±4,52° (0–10°)
Smith machine squats			
All athletes 57	94,42° ±4,78° (90–109°)	106,28° ±9,14° (90–123°)	4,46° ±4,80° (0–19°)
Male athletes 31	94,81° ±5,36° (90–109°)	107,00 ±°8,35° (90–123°)	4,84° ±5,38° (0–19°)
Female athletes 26	93,96° ±4,02° (90–105°)	105,42° ±10,11° (90–123°)	4,00° ±4,06° (0–15°)

Table 2. The differences and the significance of the differences in the mean hip, knee, and ankle angles in different squats between male and female athletes, between squats with and without added weight

Samples of athletes being compared	The knee joint flexion angle	The hip joint flexion angle	The ankle joint dorsiflexion or extension angle (same as tibial shaft forward tilt angle)
1	2	3	4
The differences and the significance of the differences by Student's test in horizontal squats			
Male and female athletes	2,25° Insignificant, p = 0,1153	3,21° Insignificant, p = 0,0829	2,24° Insignificant, p = 0,0692
All athletes without and with a barbell	*–4,56°* *Significant, p = 0,0013*	0,31° Insignificant, p = 0,8688	*–3,11°* *Significant, p = 0,0106*
Male and female athletes without a barbell	*4,71°* *Significant, p = 0,0232*	2,12° Insignificant, p = 0,4030	2,6° Insignificant, p = 0,1314
Male and female athletes with a barbell	–0,8° Insignificant, p = 0,6509	4,36° Insignificant, p = 0,1145	1,48° Insignificant, p = 0,3844
The differences and the significance of the differences by Student's test in half-squats			
Male and female athletes	–5,66° Insignificant, p = 0,2718	5,59° Insignificant, p = 0,2880	–3,26° Insignificant, p = 0,0918
All athletes without and with a barbell	–10,33° Insignificant, p = 0,1327	–0,71 Insignificant, p = 0,9307	*–9,25* *Significant, p = 0,0002*

1	2	3	4
The differences and the significance of the differences by Student's test in lunges			
Male and female athletes	1,81° Insignificant, p = 0,3049	1,79° Insignificant, p = 0,4190	1,58° Insignificant, p = 0,3811
All athletes without and with a barbell	*4,15°* *Significant, p = 0,0381*	–3,86° Insignificant, p = 0,1279	*4,37°* *Significant, p = 0,0326*
The differences and the significance of the differences by Student's test in Smith machine squats			
Male and female athletes	0,85° Insignificant, p = 0,5108	1,58° Insignificant, p = 0,5214	0,84° Insignificant, p = 0,5160

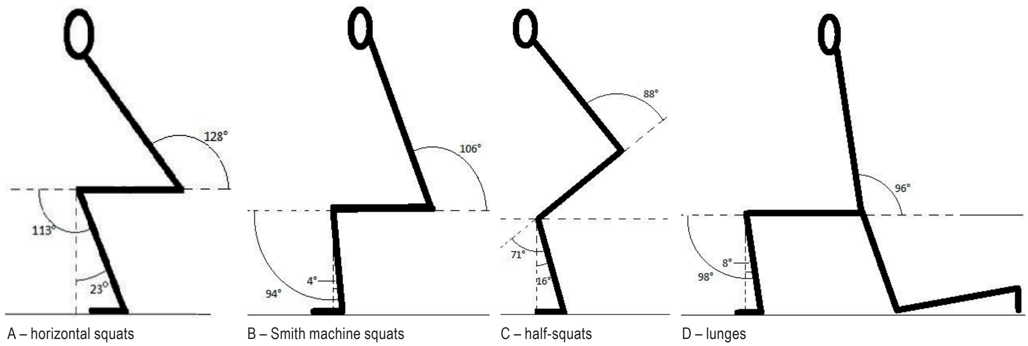

Figure 1. Schematic drawing of the lower extremity joints mean angles in different squats

In addition to defining absolute values of flexion angles in the joints of the lower extremities in different squats, we also found that the knee joint flexion and the ankle joint dorsiflexion angles in a horizontal squat with a barbell are significantly larger (by a mean of 4.56° and 3.11° respectively) than in squats without added weight. The same trend was observed for half-squats, with an even greater difference. However, the last one is statistically significant only for dorsiflexion in the ankle joint (9.25° difference at p = 0.0002). Exactly the converse situation was observed in lunges when the knee joint flexion and ankle dorsiflexion angles are significantly lesser in barbell squats (by a mean of 4.15° and 4.37°, respectively). We also detected a slightly greater knee flexion angle in horizontal squats in men, which became significantly higher (by a mean of 4.71° at p = 0.0232) when using added weight (barbell). Thus, the knee flexion angle in horizontal barbell squats in male athletes is significantly larger than in female athletes. The hip joint flexion angle and the tibia forward tilt angle in horizontal squats in men are also greater than in female athletes, but the difference is insignificant.

Discussion

Our data correspond well to the study of powerlifters and weightlifters conducted by Wretenberg et al. (1996). However, we confirmed these with a larger sample of athletes with and without added weight, additionally evaluated tibia forward tilt, and investigated joint angles in the other types of squats also.

There are several methods for angles measuring in joints, so it is essential to know and understand which method the researcher uses to interpret the results adequately. Thus, in their generally interesting and valuable study, Lorenzetti et al. (2012) did not indicate either the method of measuring the angles they used or the depth of squatting. Regarding the angles by their values, we can guess that the angle between the shin and the thigh was most likely measured not with the neutral-zero method. In addition, we still do not have data on the depth of squats, and the study was conducted on students, not athletes. It is interesting to know the joint angles in the horizontal squats performed specifically by the athletes accustomed to performing it with the ideal technique regularly with weight and under a coach's control.

The study shows how different the lower extremities joint angles are among the athletes of strength sports with considerable experience in performing these variants of squats. We can use the means for computer-generated simulation of the tensile load in the joint anatomical elements during squats, which are part of the physical therapy and rehabilitation treatment of patients with the lower extremities joint injuries and diseases. We can also use these data to imitate squats in a direct stress machine for the tensile load test of anatomical structures and ligament grafts, strength evaluation of the fixation of grafts and fractures. Data on the angles range and differences between male and female athletes, between squats with and without barbells allow better adaptation of the physical therapy and rehabilitation program to the characteristics of injury, surgery, and functional purpose of patients.

Research limitations. A limitation of our study was the lack of strict standardization of athletes according to athletic disciplines and professional level. At the same time, we have restricted ourselves to strength sports and separately specified the joint angles in barbell squats and squats without a barbell. Another limitation of our study is the involvement of all athletes only for horizontal squats. Not all the athletes performed the other types of squats because of the later decision to include them in the study. Some athletes dropped out of further research due to injuries, illness, quarantine, social reasons, or not regularly practicing a particular type of squat. It could not be a model for their implementation and research.

Conclusions

Horizontal squats produce greater knee, hip, and ankle angles than half-squats, Smith machine squats, and lunges. There is a small but significant difference in the knee and ankle joint angles between the barbell and bodyweight horizontal squat and between the barbell and bodyweight lunges. The difference in join angles between male and female athletes is significant only for the knee flexion in horizontal barbell squats.

The exact mean joint angles and their extremes obtained in this study are essential for the further joint structural elements stress simulation studies with either a computational model or a direct stress machine.

References

Endo, Y., Miura, M., Sakamoto, M. (2020). The relationship between the deep squat movement and the hip, knee and ankle range of motion and muscle strength. *Journal of physical therapy science*, *32* (6), 391–394. DOI: 10.1589/jpts.32.391.

Escamilla, R.F. (2001). Knee biomechanics of the dynamic squat exercise. *Medicine and science in sports and exercise*, *33* (1), 127–141. DOI: 10.1097/00005768-200101000-00020.

Fry, A.C., Smith, J.C., Schilling, B.K. (2003). Effect of knee position on hip and knee torques during the barbell squat. *The Journal of Strength and Conditioning Research*, *17* (4), 629–633. DOI: 10.1519/1533-4287(2003)017<0629:eokpoh>2.0.co;2.

Li, X., Adrien, N., Baker, J.S., Mei, Q., Gu, Y. (2021). Novice Female Exercisers Exhibited Different Biomechanical Loading Profiles during Full-Squat and Half-Squat Practice. *Biology*, *10* (11), 1184. DOI: 10.3390/biology10111184.

Lorenzetti, S., Gülay, T., Stoop, M., List, R., Gerber, H., Schellenberg, F., Stüssi, E. (2012). Comparison of the angles and corresponding moments in the knee and hip during restricted and unrestricted squats. *The Journal of Strength and Conditioning Research*, *26* (10), 2829–2836. DOI: 10.1519/JSC.0b013e318267918b.

Lorenzetti, S., Ostermann, M., Zeidler, F., Zimmer, P., Jentsch, L., List, R., Taylor, W.R., Schellenberg, F. (2018). How to squat? Effects of various stance widths, foot placement angles and level of experience on knee, hip and trunk motion and loading. *BMC sports science, medicine & rehabilitation*, *10*, 14. DOI: 10.1186/s13102-018-0103-7.

McKean, M., Burkett, B.J. (2012). Knee behaviour in squatting. Journal of Australian Strength and Conditioning, *20* (2), 23–36.

Myer, G.D., Kushner, A.M., Brent, J.L., Schoenfeld, B.J., Hugentobler, J., Lloyd, R.S., Vermeil, A., Chu, D.A., Harbin, J., McGill, S.M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and conditioning journal*, *36* (6), 4–27. DOI: 10.1519/SSC.0000000000000103.

United States Powerlifting Association. (2016). United States Powerlifting Association Technical Rules. USPA Rulebook v010116. Retrieved from https://www.sunflowergames.com/images/PDF/2017_Rules/USPA-Rulebook.pdf

Wretenberg, P., Feng, Y., Arborelius, U.P. (1996). High- and low-bar squatting techniques during weight-training. *Medicine and science in sports and exercise*, *28* (2), 218–224. DOI: 10.1097/00005768-199602000-00010.

Zawadka, M., Smolka, J., Skublewska-Paszkowska, M., Lukasik, E., Gawda, P. (2020). How Are Squat Timing and Kinematics in The Sagittal Plane Related to Squat Depth? *Journal of sports science & medicine*, *19* (3), 500–507.

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