RESEARCH ARTICLE

Knee and Ankle Biomechanics during Squatting with Heels on and Off of the Ground, with and Without Weight Shifting

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Abstract

Various postures are often employed when squatting; the two most common being the Asian Squat, which involves the heels remaining on the ground throughout the squat, and the Catcher’s Squat in which the heels are raised from the ground throughout the movement. Also, during periods of long squatting activities it is common for people to shift their weight to maintain comfort. The purpose of this study was to examine the biomechanics of the knee and ankle joints and the associated muscular activities during deep squatting with and without body weight shifting while the heels were both on and off the ground.

Data were collected from eight volunteers using an integrated human motion analysis system. On average lifting the heels off the ground (Catcher’s squat) caused the knee extension moments and the ankle plantar flexion moments to increase compared to keeping the heels on the ground (Asian Squat). EMG data show that the tibialis anterior muscle activities were larger during the Asian squat than during the catcher’s squat. Activities from the medial and lateral gastrocnemius were larger during the catcher’s squat. The hamstrings muscles experienced very little activity during both squats.

Shifting weight caused the knee extension moments to increase during both the Asian and Catcher’s squats, but did not significantly change the knee flexion angles. Also, the ankle plantar flexion moments and the maximum ankle dorsiflexion increased with weight shifting during both squats.

Keywords: Catcher’s Squat, Asian Squat, Human Motion Analysis, EMG, Deep Squat

Abbreviations: TKR: Total Knee Replacements; EMG: Electromyography; MVC: Maximum Voluntary Contraction; ASIS: Anterior-Superior-Iliac-Spine; GM: Gluteus Maximus; VM: Vastus Medialis; VL: Vastus Lateralis; BF: Biceps Femoris; TA: Tibialis Anterior; MGN: Medial Gastrocnemius; LGN: Lateral Gastrocnemius

Introduction

Deep squatting is an activity that is used in the daily lives of many people such as in sports, gardening, bending down to grab something, and working on or near the ground, or just to relax and pass time. In Asian cultures, deep squatting requires a flexion angle range from 130° to 165° as when working close to the ground, reading, dining, praying, using the toilets, or just waiting in a location [1]. Sitting using the western style chair has been widely accepted into the Asian culture as the global economy is bringing more contacts between Asian and Western cultures. However, the western toilets are not widely accepted by the Asian culture as Asians are more comfortable using an Asian style toilet than a Western style one [2]. The Asian style toilets require the feet to be flat, and the individual to be in a prolonged deep squat throughout the elimination process [3]. It has been suggested that using the Asian style toilets has numerous health benefits [3]. The deep squatting posture assumed while using the Asian style toilets makes the elimination process faster and more complete reducing fecal stagnation which is a prime cause for colon cancer [2, 4]. Chronic straining is also reduced while using the Asian style toilets which reduce the risks for hernias, diverticulosis, and pelvic organ prolapse [4]. As a result, the Continence Foundation of Australia has recommended the ‘near squat position’ with knees above the Anterior Superior Iliac Spine [5] to make defecation easier.

Moreover, patient satisfaction following total knee replacements (TKR’s) is traditionally measured by how successful these procedures are in reducing the pain associated with severe arthritis. However, kneeling or squatting would be unachievable following these procedures as knee flexion up to 165° is unreachable. The design of TKR’s has evolved to focus on providing individuals who need maximum flexion with products that address these needs. Similarly, ankle motions are very limited following ankle replacements. Yet, these procedures and treatment modalities are considered successful in the Western culture if they alleviate pain and allow patients to walk or sit on a chair [6]. However, due to the limited resulting range of motion, these procedures are not widely accepted in

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the Asian culture, even if they lessen the pain associated with the decease of the joints. This is because daily activities in the Asian culture require deep squatting; the patient is not able to obtain full flexion and/or full ankle range of motion following these procedures, and hence will not be able to maintain the life style they had preoperatively. Furthermore, the benefits of attaining deep flexion following a TKR have been recently recognized in the Western culture. Developing total knee and ankle replacements that allow maximum range of motion has been challenged by the limited amount of quantitative data that describe the kinematics and kinetics data of these two joints during deep squatting [7-9].

Up to 40 posture variations have been identified in the literature for squatting [10]. The two most common postures employed when deep squatting are the Asian Squat, which involves the heels remaining on the ground throughout the squat, and the Catcher’s Squat (also the wicket-keeper squat in cricket) in which the heels are raised from the ground throughout the movement [1, 3, 11].

Many studies have been performed to study the biomechanics and muscle activities during squatting activities where the knee angle is between 0° and 100° [12, 13]. Some previous studies have also looked at different aspects of the deep squatting activities. Butler et al. [14] did a study to see if different biomechanical strategies were used by volunteers who scored differently on the Functional Movement Screen deep squat test. Fukagawa et al. [15] reported the changes in the kinematics of the hip, knee, and ankle joints during a deep squat as a result of age. The effects of the positions of the heels during deep squatting have not been largely studied, but some previous work has shown that the squatting with the heels off of the ground produces higher joint moments in the knee [4]. Toutoungi et al. [16] reported the forces in the cruciate ligaments during a squat with heels both on and off the ground. Desloovere et al. [17] reported on the reliability of motion capture measurements on various movements, including both mild and deep squatting, while allowing the heels to be lifted from the ground if needed. Thambyah [18] studied the tibiofemoral joint contact forces during squatting in Asian population.

Many common squatting activities require squatting for prolonged periods of time. Most previous studies about squatting have not been for either the weighted squat exercise or deep squatting (70° of flexion) and half squatting (40° of flexion) and the associated muscular activities during deep squatting while the heels were both on and off the ground and with and without body weight shifting.

Methods

Experimental protocol

A testing protocol was designed to collect biomechanics data from individuals performing squatting with heels on and off the ground, with and without body weight shifting. Body shifting was performed in order to mimic the possible situations that an individual may experience if squatting is an activity that is regularly performed for longer periods of time. The testing protocol was approved by the Institutional Review Board at the University of Toledo (IRB#107636).

Ten Raptor-E digital cameras [21] from Motion Analysis, Inc. were used to capture the motion data at 120 Hz. Two Optima digital force platforms from Advanced Mechanical Technology, Inc. were used in conjunction with the cameras to collect ground reaction force data at 720 Hz. Reflective markers were placed on the surface of the skin in order to identify key landmarks of the body for motion analysis. Trigno EMG sensors from Delsys, Inc. were placed over four muscle groups on the legs to capture the muscle activity during the squatting activities at 720 Hz. Cortex software [22] from Motion Analysis, Inc. was used to simultaneously collect the motion data from the cameras, the ground reaction forces from the force platforms, and the voltage data from the EMG sensors.

Four male volunteers and four female volunteers were recruited from the student population at the University of Toledo to participate in this study. The age of the male volunteers ranged...
from 19 to 27 years old, with an average age of 21.75 years. The height of the male volunteers ranged from 69 to 73 inches, with an average height of 71.125 inches. The age of the female volunteers ranged from 19 to 23 years old, with an average age of 20.7 years. The height of the female volunteers ranged from 63 to 68.5 inches, with an average height of 66.188 inches. Before testing, each volunteer was given an explanation of the test, the risks, and the benefits in accordance with the IRB protocol. Each volunteer was then given a demonstration of the test and had the opportunity to ask questions before signing a consent form for participation in the study.

Ten EMG sensors were placed on each volunteer prior to testing. Each EMG sensor was placed over the body of the selected muscle as described by Basmaian and Blumenstein [23] EMG sensors were placed on the rectus femoris, the biceps femoris, the tibialis anterior, and the lateral and medial heads of the gastrocnemius on both the right and left legs. Prior to EMG sensor placement each site was cleaned with a cotton swab and 70% isopropyl alcohol to remove any debris that may interfere with the EMG recordings. Once the EMG sensors were placed over the muscles, a series of maximum voluntary contraction (MVC) tests were done. These tests were done to get an average reading from each EMG sensor when the muscles were working at the maximum amount of voluntary contraction so that they could be used to normalize the readings from the squatting tests.

To get the average MVC value from the biceps femoris the volunteer would lie on their stomach. The volunteer would then contract the biceps femoris by attempting to flex the knee while their leg was held in place by a large resistance. The MVC test was done three times, once with a starting knee flexion of 0°, once with a starting knee flexion of 30°, and once with a starting knee flexion of 60°. This was done so that one average value could be found over the normal range of motion. To record the MVC tests for the rectus femoris the volunteer was seated in a chair. The volunteer would then contract the rectus femoris as hard as they could by trying to extend the knee while their leg was held in place by a large resistance. The MVC test was done three times, once with a starting knee flexion of 90°, once with a starting knee flexion of 60°, and once with a starting knee flexion of 30°. To record the MVC tests for the tibialis anterior the volunteer was seated in a chair. The volunteer would then contract the tibialis anterior as hard as they could by trying to dorsiflex the ankle while their foot was held in place by a large resistance. The MVC test was done three times, once with a starting ankle flexion of 0°, once with a starting ankle plantar flexion of 30°, and once with a starting ankle dorsiflexion of 30°. To record the MVC tests for the gastrocnemius the volunteer was standing with their knee resting on a chair. The volunteer would then contract the gastrocnemius as hard as they could by trying to plantarflex the ankle while their foot was held in place by a large resistance. The MVC test was done three times, once with a starting ankle flexion of 0°, once with a starting ankle plantar flexion of 30°, and once with a starting ankle dorsiflexion of 30°.

Once the MVC tests were finished the volunteers were instrumented with twenty-one reflective markers. These reflective markers were used to identify the key landmarks needed to reconstruct the lower half of the Helen-Hayes model [24] used for motion analysis. One marker was placed on the right anterior-superior-iliac-spine (ASIS), the left ASIS, the sacrum, the lateral epicondyle of the right knee, the medial epicondyle of the right knee, the lateral malleolus of the right ankle, the medial malleolus of the right ankle, the calcaneus of the right foot, the 2nd metatarsal of the right foot, the lateral epicondyle of the left knee, the medial epicondyle of the left knee, the lateral malleolus of the left ankle, the medial malleolus of the left ankle, the calcaneus of the left foot, and the 2nd metatarsal of the left foot. One marker was also placed along the lateral side of the anterior of the thigh and the lateral side of the anterior of the shank for both the right and left legs. Additionally, one marker was placed on both the right and left greater trochanter in order to ensure that the virtual markers for the right and left hip calculated by Cortex were in line with the physical anatomy of the volunteer.

Data Collection

The volunteer stood first on each of the two force platforms for two seconds to collect body weight. A series of squatting activities were then performed. The volunteer stood off of the force platforms with one foot in front of each prior to recording. For each activity the volunteer was instructed to step onto the force platforms, putting one foot near the center of each platform. For the first activity, the Asian squat, the volunteer was given verbal instructions to perform a squat with their heels on the ground. The volunteer would then squat down as far as they could while maintaining contact between their heels and the ground, and then would rise back to a standing position in one motion. For the second activity the volunteer was given verbal instructions to perform a Catcher’s squat, a squat with their heels off of the ground. The volunteer would then rise onto the balls of their feet as they squatted down as far as they could, and then would rise back to a standing position in one motion. For the third activity the volunteer was instructed to repeat the Asian squat with the addition of weight shifting. The volunteer would then squat down as far as they could while maintaining contact between their heels and the ground. Once the volunteer reached a stable position they were instructed to shift their weight onto their right leg. After shifting their weight as far as they were comfortable with they were instructed to shift their weight onto their left leg. After shifting their weight onto their left leg as much as they were comfortable with the volunteer was instructed to return to a neutral position with their weight evenly distributed between their legs. Once the volunteer evenly distributed weight they were instructed to return to a standing position. Once they returned to a steady and stable standing position they were given verbal instructions to step off of the force platforms. For the final activity the volunteer was instructed to repeat the Catcher’s squat with weight shifting in the same manner as the Asian squat with weight shifting. Each trial was repeated until a total of five squatting tests were completed without any unwanted events such as loss of balance.
Data Processing

The data for each test was trimmed to include only the data from the time right before the volunteer began the descent phase of the squat up until the time right after the volunteer completed the ascent phase of the squat. After trimming the data from each recording a low pass 4th order Butterworth filter with a cut off frequency of 6Hz was applied to the data. The data from the markers on the body were used to calculate the joint centers based on anthropomorphic data within the Cortex software [22]. Once the segments were defined, the Kin Tools RT toolset within the Cortex software was used to calculate joint angles and moments from the marker and force platform data, and the data were exported to Excel for further analysis. The processed force platform ground reaction forces and EMG signals were also exported to Excel for further analysis.

The EMG data were imported into EMG works software [25] from Delsys® Inc. The EMG data were filtered using a band pass filter with a lower cutoff frequency of 20 Hz and an upper cutoff frequency of 355 Hz. The linear envelope for each trial was found using the root-mean-square method with a window length of 0.125 seconds and an overlap of 0.0625 seconds. The processed EMG data were then exported back into Excel for further analysis. The MVC trials were used to find the average maximum voluntary muscle activity for each muscle in each position, and to find the average maximum voluntary muscle activity over the range of motion for each muscle. Once the average maximum voluntary muscle activity for each muscle was determined, the EMG data from all squatting trials were normalized with respect to the individual muscles’ voluntary maximum contraction. The body weight of the volunteer was then used to normalize the individual joint moments to the volunteer’s mass. The time of the squatting activity was also normalized by the time it took to perform the entire activity in order to compare the volunteers to each other based on the percentage of the squatting activity completed.

Results

The squatting exercise was found to be symmetrical between the right and left leg, with both legs showing the same trends and similar results. Because of this, only data for one leg is shown. When the volunteer shifted weight to the right leg the vertical ground reaction force of the right leg increased while the ground reaction force of the left leg decreased. Conversely, when the volunteer shifted weight to the left leg the vertical ground reaction force of the left leg increased while the ground reaction force of the right leg decreased. Approximately, without shifting, the weight was equally distributed between the right and the left legs. When the weight was shifted to one side, the vertical component of the ground reaction force of the leg on that side increased by 60% (from 0.5 body weight to 0.8 body weight) and that on the other side decreased by 60% (from 0.5 body weight to 0.2 body weight). Paired t-tests with an alpha of 0.05 were used to determine statistical differences. Comparisons were done between the Asian squats and the Catcher’s squats and between weight-shifting squats for the average of all volunteers. Additionally, comparisons were done between the male and female volunteers for each squatting condition. In all figures, sections A-B of the graphs show the descent phase of the squat, while sections B-C show the ascent phase.

Knee Joint Kinematics and Kinetics

In general, and in both types of squat, the knee extension moment increased with knee flexion. Figure 1.a shows that without body weight shifting, the average maximum knee extension moment during the Asian squat reached 0.66 Nm/kg with an average maximum knee flexion angle of 121.2°. Figure 1.b shows that during the Catcher’s squat, and without body weight shifting, the average maximum knee extension moment was 0.76 Nm/kg with an average maximum knee flexion angle of 131.6°. This corresponds to an increase of 15.2% in the knee extension moment and an increase of 8.6% in the knee flexion angle when the posture changed from the Asian squat to the Catcher’s squat. The statistical analysis has shown that there was a statistically significant difference in knee extension moments due to lifting the heels off the ground. Also, Figures 1.a and 1.b show that during body weight shifting the average maximum knee extension moment

![Figure 1: Average knee extension moments during the Asian and catcher squats with and without weight shifting. (a): Average knee extension moments during the Asian squat with and without weight shifting. (b): Average knee extension moments during the Catcher squat with and without weight shifting.](image-url)
for the Asian squat increased 39.4% to 0.92 Nm/kg and for the Catcher’s squat increased 61.8% to 1.23 Nm/kg. There was a statistically significant difference in knee extension moments due to shifting body weight.

**Ankle Joint Kinematics and Kinetics**

Figures 2.a and 2.b show how the ankle plantar flexion moment changes with ankle flexion angle during the Asian and Catcher’s squats, respectively. The patterns were very different. The ankle angle generally started in a plantar flexed position. Once the squatting activity started the ankle angle would decrease in plantar flexion, and then switch to an increasing dorsiflexion angle. During the Asian squats, the ankle plantar flexion moment decreased as the plantar flexion angle decreased during the descent phase (portion AB on the graphs) and as the dorsiflexion angle decreased during the ascent phase (portion BC on the graphs). During the Catcher’s squat, the ankle plantar flexion moment increased to a maximum and then remained almost constant during the descent phase as the dorsiflexion angle decreased until the heels were placed back onto the ground. Figure 2.a shows that without body weight shifting, the average maximum ankle plantar flexion moment during the Asian squat reached 0.2 Nm/kg with an average maximum ankle plantar flexion and dorsiflexion angles of 15.2° and 9.7°, respectively. Figure 2.b shows that during the catcher’s squat, and without body weight shifting, the average maximum ankle plantar flexion moment was 0.504 Nm/kg with an average maximum ankle plantar flexion and dorsiflexion angles of 13.3° and 7.6°, respectively. This corresponds to an increase of 152% in the ankle plantar flexion moment when the posture changed from the Asian squat to the Catcher’s squat. The statistical analysis has shown that there was a statistically significant difference in ankle plantar flexion moments due to lifting the heels off the ground. Also, Figures 2.a and 2.b show that during body weight shifting the average maximum ankle plantar flexion moment for the Asian squat increased 152% to 0.51 Nm/kg and for the Catcher’s squat increased 31% to 0.66 Nm/kg. There was a statistically significant difference in ankle plantar flexion moments due to shifting body weight. Figure 2.a also shows that during the Asian squat, and with body weight shifting, the maximum ankle plantar flexion and dorsiflexion angles were 14.1° and 15.8°, respectively. These data show that the dorsiflexion angle increased 66% due weight shifting during the Asian squat. Furthermore, Figure 2.b shows that during the catcher squat, and with body weight shifting, the maximum ankle plantar flexion and dorsiflexion angles were 13.4° and 9.9°, respectively. These data show that the dorsiflexion angle increased 30% due weight shifting during the Catcher.
squat. There was a statistically significant difference in ankle dorsiflexion angle due to shifting body weight.

**Muscle Activities**

Figures 3 through 6 shows how the muscle activities change with knee flexion angle during the Asian and Catcher’s squats. The activity of the quadriceps muscles generally increased as the knee flexion angle increased as shown in figure 3. On average the quadriceps muscles experienced more activity during the Asian squat than during the Catcher’s squat. There was an increase of 21% in the maximum quad activity during the Asian squat when compared to the catcher’s squat. Body weight shifting did not seem to alter the maximum quadriceps activity.

The hamstrings muscle experienced very little activity during both Asian and catcher’s squats. The maximum detected hamstrings muscle activity was about 14% MVC. Figure 4 shows that the tibialis anterior muscle activity generally increased as the knee flexion angle increased. As shown in figures 4.a and 4.b, the tibialis anterior muscle activities were much larger during the Asian squat than during the catcher’s squat. The tibialis anterior had an increase of 38% in the average muscle activity during the Asian squat.

Figures 5 and 6 show that both lateral and medial gastrocnemius muscles activities were relatively steady throughout all squatting activities and much larger during the catcher’s squat than during the Asian squat. The lateral gastrocnemius had an increase of 100% in average muscle activity during the Catcher’s squat. The medial gastrocnemius had an increase of 84% in the average muscle activity during the Catcher’s squat. There were statistically significant differences found in the maximum and average quadriceps activities, the maximum and average tibialis anterior activities, and the average activities of both the medial and lateral gastrocnemius muscles. Body weight shifting did not statistically change the amount of muscle activities experienced in any muscle during any of the trials.

**Discussion**

Various postures are often employed when squatting; the two most common being the Asian Squat, which involves the heels remaining on the ground throughout the squat, and the Catcher’s Squat in which the heels are raised from the ground throughout the movement. Additionally, during periods of long squatting activities it is common for people to shift their weight to maintain comfort. The purpose of this study was to
examine the biomechanics of the knee and ankle joints during a deep squatting activity while the heels were both on (Asian squat) and off the ground (Catcher’s squat). The effect of weight shifting while holding the squatting was also examined.

It was found that knee extension moments and ankle plantar flexion moments were statistically significantly larger during the Catcher’s squat than during the Asian squat. This can be explained by studying both postures depicted in figure 7 [26]. During the Catcher’s squat, lifting the heels off the ground causes the center of pressure to move more anteriorly and the ankle joint to move more proximally. This will cause an increase in the moment arm of the ground reaction force around the ankle joint, thus producing larger plantar flexion moments. Also, in the Catcher’s squat, the knee joint moves anteriorly away from the center of mass of the body and away from the center of pressure. Additionally, the center of mass is lifted further away from the knee superiorly. This causes an increase in the moment arm of the ground reaction force around the knee joint, thus producing larger knee extension moments.

It was also found that shifting weight caused the knee extension moments and ankle plantar flexion moments to significantly increase during both Asian and Catcher’s squats. As body weight shifted to one side of the body the joint moments increased on that side. As body weight shifted away from one side of the body the joint moments decreased on that side. The Catcher’s squat caused a greater increase in the knee extension moment when weight shifting occurred. This could be due to the difference in moment arms between the two positions. Also the maximum ankle dorsiflexion increased with weight shifting during both squats. When weight is shifted onto one leg, the ankle begins to buckle under the added weight causing a greater dorsiflexion.

Caterisano et al. [27] measured the relative contribution of the vastus medialis (VM), the vastus lateralis (VL), the biceps femoris (BF), and the gluteus maximus (GM) while performing squats at 3 depths. They reported that the BF has about 9% percent contribution during the descent phase and 15% during the ascent phase of the full squat. These results are in agreement with our findings that the hamstrings muscle activities were minimal during both squatting activities. We are not able to make one to one comparison because we did not measure the VMO, VL or the GM activities. However, we are able to make a qualitative comparison because our measured hamstrings activities were minimal during our tested conditions.

The EMG activities also show that the tibialis anterior (TA) muscle activities during the catcher’s squat were smaller than those during the Asian squat, and the medial and lateral gastrocnemius (MGN) and (LGN), respectively, were larger in the catcher’s squat than during the Asian squat. This is consistent with our findings that the plantar flexion moments were larger in the catcher’s squat.

Ninos et al. [28] reported that the quadriceps muscle activity increased with knee flexion angle when squatting from 10 to 60 degrees. Also, Wilk et al. [29] reported that the extension torque was at a maximum during squatting when the knee was flexed from 74 to 102 degrees. These results are in agreement with our findings that knee extension moments and quadriceps muscle activities increased with knee flexion angle during both types of squat.

Our findings show that the rectus femoris activities are larger during the Asian squat than during the Catcher’s squat. This
needs to be explained as it appears contradictory to our finding that knee extension moments are larger during the Catcher’s squat. This is related to the limitation of our study in that we did not measure the GM, VM and VL activities. As mentioned earlier, Caterisano et al. [27] measured the relative contribution of the VM, the VL, the BF and the GM during squat. They reported that the GM, the VM and the VL had 13%, 43% and 34% contribution, respectively, in the descent phase of the squat and 35%, 20% and 29% contribution, respectively, if the ascent phase of the squat. They also reported that the GM becomes more active as the knee flexion angle increases during squatting. Schaub and Worrell [30] reported that the maximum voluntary isometric contraction for the squat exercise for the RF, VM, VL and Hamstrings as 40%, 90%, 70% and 10%, respectively. Comfort and Kasim [31] report that EMG studies show that GM provide a bigger contribution than the VM and the VL during full depth squat to 125 degrees of knee flexion. Dionisio et al. [20] reported that the VMO activities were greater than the VML activities which were greater than the RF activities during downward squatting; the VMO activities being around 4 times the RF activities. It has also been reported by Bryanton et al. [32] the relative contribution of the GM versus hamstrings will impact quadriceps activities during squatting. They proposed a hip extensor strategy where hamstring co-activation is minimized during squatting. This is in agreement with our findings of minimal hamstrings activities during both types of squat. We hypothesize that the VM and VL activities will increase during the catcher’s squat to account for the increased knee extension moments compared to the Asian squat. Future work needs to be done to quantify the VM, VL and GM activities during both types of squat.

Due to the increase in joint moments, more stress may be placed on the joints when squatting in the Catcher’s position for extended periods of time. Weight shifting should be avoided if possible so that additional stresses are not put on the knee and ankle joints. Therefore, it is recommended that the Asian squat be considered when squatting for extended periods of time. This may take more reconditioning to get accustomed to due to the change in posture. However, it must be practiced and built up so that weight shifting does not occur to maintain comfort in an unfamiliar squatting position. Weight shifting should be avoided if possible, and should instead be replaced with standing in order to relieve the joints of the increased moments.

Acknowledgments

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