Impact of Toe-Out Squat Variations on Lower Limb Joint Angles and Forces

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INTRODUCTION

Squatting is a fundamental movement widely utilized in daily life, sports, and rehabilitation, yet variations in foot positioning during squats have remained an area of biomechanical interest. Outward foot positioning, in particular, has been associated with changes in lower limb mechanics, including potential effects on joint range of motion (ROM) and vertical ground reaction forces (GRFs) [1]. Understanding these variations is critical for optimizing squat performance and reducing stress on the lower limb joints. Biomechanical tools such as the VICON Motion Capture System and the Kistler Piezoelectric Force Plate allow for precise measurement of joint kinematics and GRFs, providing valuable insights into the effects of different squat techniques [2]. The purpose of this study was to analyze and compare the ROM of the hip, knee, and ankle joints, as well as vertical GRFs, during squats performed with feet in a neutral position and with feet pointing outward. It has been hypothesized that outward foot positioning would reduce knee valgus angles while increasing hip external rotation and ankle dorsiflexion compared to a neutral stance.

METHODS

The subject, a 21-year-old female with a height of 175 cm and weight of 60 kg, performed three dynamic squat trials under two conditions: shoulder-width stance with feet in a neutral position (control) and shoulder-width stance with feet pointing outward. Informed consent, approved by the Research Ethics Board (REB), was obtained prior to participation. The subject wore close-fitting athletic clothing and performed all trials barefoot to ensure accurate marker visibility and eliminate external footwear support. A static trial was conducted first to establish a baseline for anatomical marker positioning. Reflective markers were placed on the subject following the Visual3D and CODA marker set guidelines, using the CODA pelvis model, thigh model 1, shank model 1, and one-segment foot model. A total of 23 reflective markers were positioned to capture the motion of the pelvis, thighs, shanks, and feet, allowing for motion tracking across six degrees of freedom (DOF) per segment.

The experimental setup included the VICON Motion Capture System (2000 Hz sampling rate; Vicon Motion System Ltd., Oxford, UK) and the Kistler Piezoelectric Ground Reaction Force (GRF) Platform (2000 Hz sampling rate; Kistler, Switzerland), synchronized to record joint kinematics and GRFs simultaneously. The lab space was calibrated using a calibration wand to align the VICON system's cameras along the XYZ axes. Reflective materials within the experimental space were covered, and curtains were drawn to minimize external light interference. Cameras were individually masked in the VICON Nexus software to eliminate irrelevant reflections. Calibration of the GRF platform ensured accurate measurement of forces in the vertical, medial-lateral, and anterior-posterior directions. The subject performed each trial for five seconds, with arms crossed over the chest to avoid marker obstruction. After the trials, data was processed in VICON Nexus (version 2.12.1; Vicon Motion System Ltd., Oxford, UK), where marker trajectories were reconstructed, gap-filled, and labeled. Files were exported to Visual3D (HASMotion Inc., Boyds, MD, USA) for post-processing. Marker trajectories were filtered using a low-pass Butterworth filter with a cutoff frequency of 6 Hz to minimize noise. Visual3D was used to calculate joint angles (hip, knee, and ankle) and vertical GRFs for each condition. Ground reaction force data, collected through the Kistler platform. In MATLAB R202b (MathWorks, Massachusetts, USA), the range of motion (ROM) for the hip, knee, and ankle joints, as well as vertical force profiles, were analyzed. To normalize the data, joint angles and GRFs were resampled to 101 points, representing 0-100% of the squat cycle. This normalization ensured consistency in comparing trials of varying durations. From the normalized data, the single best trial for each condition was selected based on signal clarity and reproducibility. Joint angles and GRFs were then plotted to highlight differences between the control and toes-pointing-outward conditions. The processed results were effectively analyzed to provide insights into how hip external rotation, ankle dorsiflexion, and knee valgus angles varied across conditions.

RESULTS

This figure represents the mean and standard deviation of adduction joint angles for the hip, knee, and ankle throughout the movement cycle under the toes pointing outward condition.

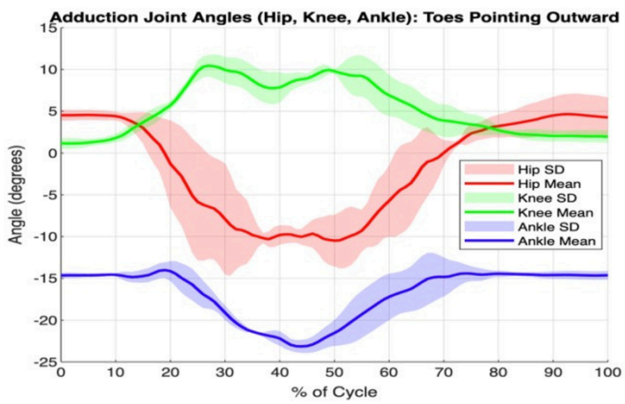

Figure 1. Adduction joint angles (hip, knee, ankle) during the squat cycle under the control condition.

This figure illustrates the mean and standard deviation of adduction joint angles for the hip, knee, and ankle across the movement cycle under the control condition.

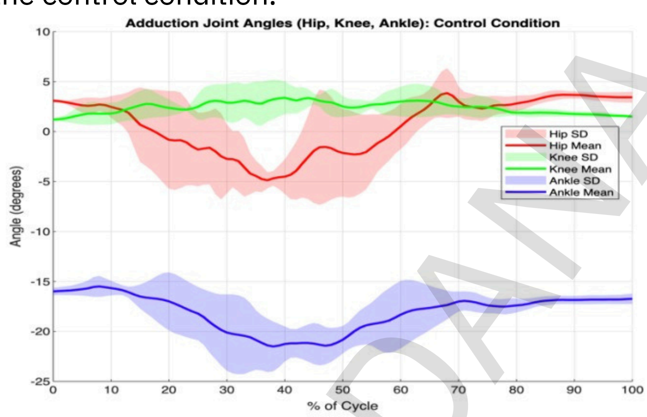

Figure 2. Adduction joint angles (hip, knee, ankle) during the squat cycle under the toes-pointing-outward condition.

This figure shows the mean and standard deviation of flexion joint angles for the hip, knee, and ankle throughout the movement cycle under the control condition.

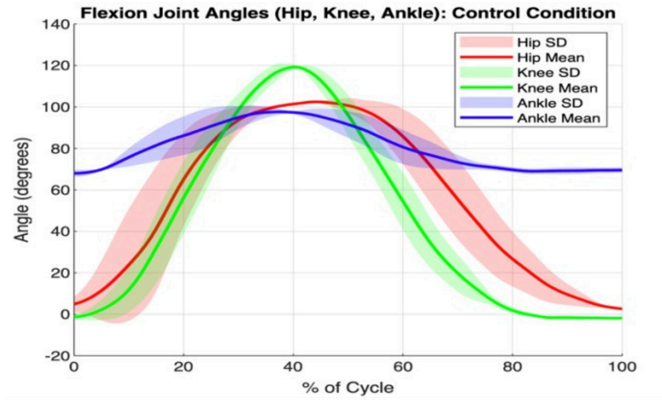

Figure 3. Flexion joint angles (hip, knee, ankle) during the squat cycle under the control condition.

This figure presents the mean and standard deviation of flexion joint angles for the hip, knee, and ankle during the movement cycle under the toes pointing outward condition.

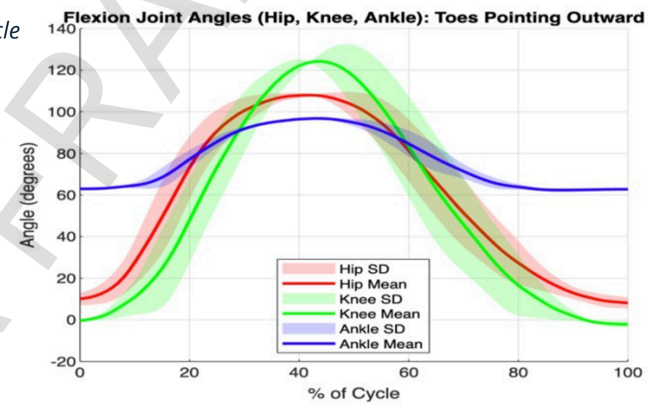

Figure 4. Flexion joint angles (hip, knee, ankle) during the squat cycle under the toes-pointing-outward condition.

This figure compares the synchronized vertical ground reaction forces across the movement cycle between the control condition and the toes pointing outward condition.

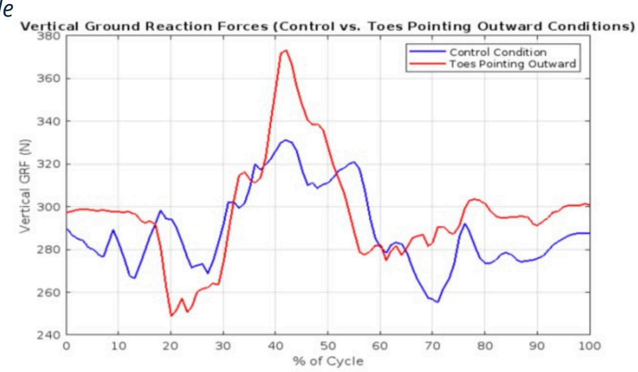

Figure 5. Synchronized vertical ground reaction forces (GRF) for the control and toes-pointing-outward conditions.

DISCUSSION

The hip joint exhibited the largest range of motion (ROM) during the squat cycle across both conditions. Peak flexion angles reached approximately 120° in the control condition, while the toes-pointing-outward condition showed a slightly lower peak at 110° [Frigure 4, Figure 3]. This slight reduction in flexion may reflect a shift in movement dynamics, with outward toe positioning encouraging greater external rotation of the hip. Notably, hip external rotation plays a vital role in aligning the femur with the tibia, thereby counteracting inward knee movement (knee valgus). Previous studies highlight how improving hip alignment can redistribute forces along the lower limb, helping to reduce knee valgus and decrease the risk of injury [3] [4]. Regarding the ankle, dorsiflexion remained consistent across both conditions, with peak ROM reaching about 80° during the deepest squat phase [Figure 1, Figure 2]. However, the toes-pointing-outward condition demonstrated smoother transitions through the squat cycle, suggesting improved alignment and force management. This observation is significant as dorsiflexion facilitates proper tibial movement over the foot, reducing lateral forces that could exacerbate knee valgus. The smoother transitions indicate better coordination and mobility in the lower limb, aligning with findings from previous research showing the importance of dorsiflexion in stabilizing knee mechanics [5] [6] [7]. The knee adduction/abduction angles provided direct insight into valgus behavior during the squat. In the toes-pointing-outward condition, knee abduction (indicative of valgus) was notably reduced, with angles approaching neutral compared to the control condition [Figure 1, Figure 2]. This reduction supports the hypothesis that outward foot positioning enhances lower limb alignment. Studies have shown that decreasing valgus stress mitigates strain on the medial knee structures, thereby lowering the likelihood of injuries like ACL tears and patellofemoral pain syndrome [8] [9].

Finally, the vertical GRF plots revealed differences in force distribution between the two conditions [Figure 5]. The toes-pointing-outward condition exhibited more concentrated and smoother peak forces compared to the control. This optimized distribution not only suggests improved joint alignment but also indicates more efficient load transfer through the lower limb. These smoother GRF profiles align with studies that associate optimized force distribution with a reduced risk of valgus-related injuries [10] [11].

CONCLUSIONS

This study highlights the biomechanical benefits of squatting with outward foot positioning. By enhancing hip external rotation, maintaining steady ankle dorsiflexion, and reducing knee valgus, this stance improves lower limb mechanics and optimizes load distribution.

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