EFFECTS OF FOOT PLACEMENT ON RESULTANT JOINT MOMENTS OF LOWER EXTREMITY JOINTS DURING SQUAT

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The purpose of this study was to investigate the effects of foot placement (stance width and foot angle) on normalized sagittal- and frontal-plane resultant joint moments (NRJM) of the lower extremity joints during the squat. Forty-two participants were recruited: male (n = 21) and female (n = 21). Three-dimensional motion analysis and inverse dynamics analysis were conducted. There was a significant interaction between the stance width and foot angle on the NRJM in the sagittal plane, whereas there were significant main effects of the stance width, foot angle, and gender on the NRJM in the frontal plane.

KEY WORDS: Squat stance, foot angle, gender, change in moment.

INTRODUCTION: The squat has been regarded as an integral part of various strength and conditioning programs and physical rehabilitation prescriptions. Poor squat technique and inappropriate squat exercise prescription, however, may result in detrimental effects on the lower extremity joints and lower back (Escamilla, Fleisig, Lowry, Barrentine, & Andrews, 2001; Fry, Smith, & Schilling, 2003). The safety of the squat has been one of the biggest concerns and a controversy concerning the proper squat technique still exists.

Foot placement can be a key determinant of the safety of the squat because lower extremity joints kinetics is substantially influenced by the foot placement during the squat (Escamilla et al., 2001). The squat can be classified into different styles based on stance width (narrow, medium, and wide) and foot angle (foot forward and outward). However, the optimum squat foot placement is still unclear among practitioners and researchers.

The lower extremity joints, including the hip, knee, and ankle joints, biomechanically function as a linked chain during the squat so it is likely that the position of each joint affects loads on the other joints. For example, a squat technique for reducing loads on the knee, such as a technique restricting the forward movement of the knee, can place more loads on the hip and lower back because the reduced knee loads can be improperly transferred to the hip and lower back (Fry el al, 2003). In order to properly perform the squat, therefore, interactions among the lower extremity joints need to be carefully considered.

The purpose of this study was to investigate the effects of foot placement (stance width and foot angle) on the NRJM in the lower extremity joints during the squat.

METHODS: Forty-two (21 males and 21 females) healthy college students with a minimum experience squat exercise of 3 years were recruited as participants (Table 1).

Table 1. Participant Characteristics

Variable	Male (n = 21)	Female (n = 21)
Mass (kg)	79.4 ± 10.5	62.0 ± 9.1
Height (cm)	178.1 ± 6.8	164.5 ± 2.7
Age (year)	26.4 ± 4.4	23.3 ± 3.3
Leg Dominance	right (20), both (1)	right (21)

Each participant performed squat trials in six different conditions (3 stance widths × 2 foot angles x 5 repetitions = 30 trials). Stance widths used were narrow stance (NS; 75% of shoulder width), medium stance (MS; 100% of shoulder width), and wide stance (WS; 140% of shoulder width). Foot angles used were forward (FF; foot pointing forward) and outward (FO; foot pointing 30° outward from the forward direction). Squat trials were performed by each participant with a weighted barbell (75% of 1 repetition maximum) placed on the top of trapezius. The motion data were collected using a 10-camera Vicon real-time motion capture system (Vicon, Centennial, Colorado, USA; 250 Hz) and two AMTI force plates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) and subsequently imported to and processed by Kwon3D Motion Analysis Suite (Version XP, Visol, Seoul, Korea). A total of 35 points (27 markers and 8 computed points including the joints) were defined and used for the analysis.

To facilitate data analysis, the squat motion was divided into four phases using five events based on the vertical center-of-mass (COM) acceleration and vertical COM position (Figure 1). Local reference frames of the lower extremity segments were defined with the X-, Y-, and Z-axis aligned with the mediolateral, anteroposterior, and longitudinal axes of the segments, respectively. Resultant joint moments (RJMs) acting on the hip, knee, and ankle joints in the sagittal and frontal planes were calculated through an inverse dynamics approach and were normalized to the participant's body mass plus barbell load. Joint coordinate systems were used in extracting the RJM components.

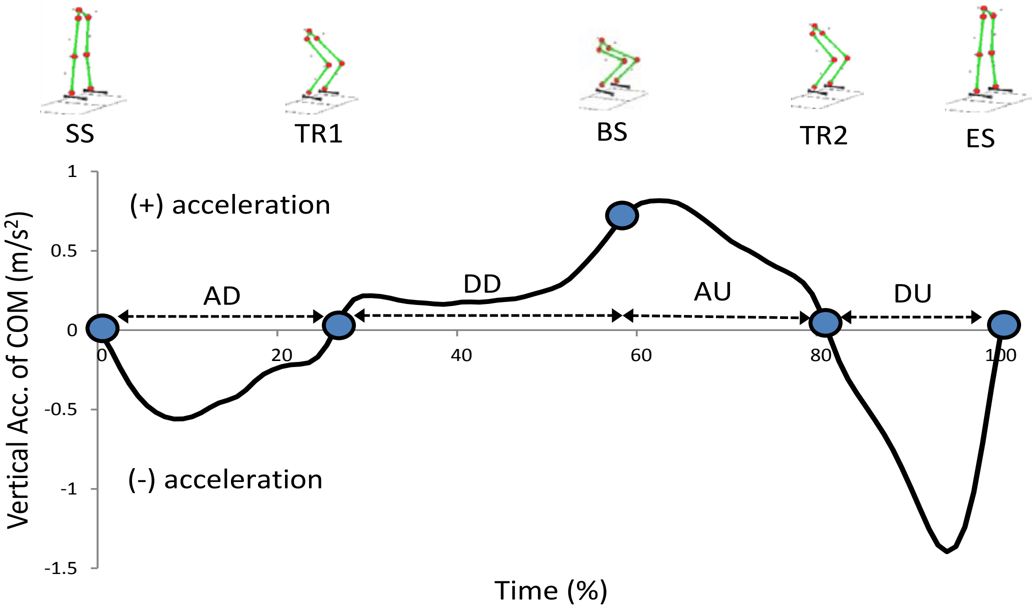

Figure 1. Squat events and phases: Start of Squat (SS), Transition 1 (TR1), Bottom of Squat (BS), Transition 2 (TR2), End of Squat (ES), Acceleration of Downward Motion (AD), Deceleration of Downward Motion (DD), Acceleration of Upward Motion (AU), and Deceleration of Upward Motion (DU).

For each variable, the peak moment values extracted from five trials in each squat condition were averaged and used in the statistical analysis. Two three-way (3 × 2 x 2) mixed designs MANOVAs were conducted to compare NRJMs in the sagittal and frontal planes separately, with the stance width (within-subject: NS, MS, and WS), foot angle (within-subject: FF and FO), and gender (between-subject: male and female) being factors. For significant factor effect or interaction, post-hoc tests were performed with Bonferroni adjustment. The level of significance was set at 0.05.

RESULTS: A significant Width*Angle interaction (Wilk's λ = 0.657, F = 3.051, p = 0.017) was observed for the sagittal-plane NRJMs (Table 2). The FO condition showed significantly higher hip extensor moment (HEX) and knee extensor moment (KEX) in the MS and WS conditions and significantly higher ankle plantar-flexor moment (AP) in the NS condition than the FF condition. Significant differences in HEX (NS < WS; MS < WS,), KEX (NS < MS; NS < WS), and AP (NS > WS) among the stance widths were also observed during the FO condition.

Table 2. Normalized sagittal-plane resultant joint moments (Nm/kg)

Variables		Foot forward			Foot out			Sig. effects
		Narrow	Medium	Wide	Narrow	Medium	Wide	
HEX	F	-0.88 ± 0.17	-0.88 ± 0.17	-0.89 ± 0.15	-0.87 ± 0.15	-0.89 ± 0.15	-0.93 ± 0.13	Width × Angle interaction
	M	-0.96 ± 0.24	-0.94 ± 0.23	-0.96 ± 0.21	-0.99 ± 0.20	-0.99 ± 0.20	-1.05 ± 0.19	
	C	-0.92 ± 0.21	-0.91 ± 0.20	-0.92 ± 0.18	-0.93 ± 0.18	-0.94 ± 0.18[c]	-0.99 ± 0.17[a,b,c]	
KEX	F	0.66 ± 0.13	0.68 ± 0.15	0.68 ± 0.13	0.68 ± 0.12	0.70 ± 0.12	0.71 ± 0.11	
	M	0.73 ± 0.13	0.74 ± 0.15	0.73 ± 0.14	0.75 ± 0.14	0.78 ± 0.14	0.77 ± 0.13	
	C	0.70 ± 0.14	0.71 ± 0.15	0.70 ± 0.14	0.72 ± 0.13	0.74 ± 0.13[a,c]	0.74 ± 0.12[a,c]	
AP	F	-0.35 ± 0.09	-0.38 ± 0.13	-0.37 ± 0.11	-0.41 ± 0.12	-0.40 ± 0.11	-0.36 ± 0.09	
	M	-0.35 ± 0.10	-0.35 ± 0.08	-0.35 ± 0.09	-0.37 ± 0.12	-0.37 ± 0.13	-0.35 ± 0.14	
	C	-0.35 ± 0.09	-0.36 ± 0.10	-0.36 ± 0.10	-0.39 ± 0.12[c]	-0.38 ± 0.12	-0.36 ± 0.12[a]	

Abbreviations: F, female; M, male; C, combined.
[a] Significantly (p<0.05) different from the matching narrow stance condition; [b] significantly different from the matching medium stance condition; [c] significantly different from the matching foot forward condition.

Significant Width effect (λ = 0.214, F = 20.798, p < 0.001), Angle effect (λ = 0.179, F = 56.753, p < 0.001), and Gender effect (λ = 0.584, F = 8.780, p < 0.001) were observed for the frontal-plane NRJMs (Table 3). The NS condition revealed the largest hip abductor moment (HAB), knee abductor moment (KAB), and ankle everter moment (AE), followed by the MS condition, and then the WS condition. The FO condition showed significantly higher KAB and AE than the FF condition, whereas the FF condition showed a significantly higher HAB than the FO condition. The male group exhibited a significantly higher KAB than the female group.

Table 3. Normalized frontal-plane resultant joint moments (Nm/kg)

Variables		Foot forward			Foot out			Sig. effects
		Narrow	Medium	Wide	Narrow	Medium	Wide	
HAB	F	-0.30 ± 0.09	-0.26 ± 0.07	-0.25 ± 0.09	-0.28 ± 0.07	-0.24 ± 0.06	-0.21 ± 0.06	Width Angle
	M	-0.27 ± 0.07	-0.23 ± 0.07	-0.21 ± 0.09	-0.26 ± 0.07	-0.22 ± 0.07	-0.19 ± 0.08	
	C	-0.28 ± 0.08	-0.25 ± 0.07	-0.23 ± 0.09	-0.27 ± 0.07	-0.23 ± 0.07[A]	-0.20 ± 0.07[A,B]	
KAB	F	-0.12 ± 0.05	-0.10 ± 0.05	-0.08 ± 0.06	-0.16 ± 0.07	-0.14 ± 0.07	-0.12 ± 0.07	Width Angle Gender
	M	-0.19 ± 0.08	-0.17 ± 0.07	-0.15 ± 0.09	-0.27 ± 0.10	-0.24 ± 0.10	-0.22 ± 0.10	
	C	-0.16 ± 0.07	-0.14 ± 0.07	-0.11 ± 0.08	-0.22 ± 0.10	-0.19 ± 0.10[A]	-0.17 ± 0.10[A,B]	
AE	F	-0.10 ± 0.04	-0.10 ± 0.04	-0.08 ± 0.04	-0.12 ± 0.05	-0.11 ± 0.05	-0.09 ± 0.04	Width Angle
	M	-0.09 ± 0.03	-0.08 ± 0.03	-0.06 ± 0.03	-0.11 ± 0.05	-0.09 ± 0.04	-0.08 ± 0.04	
	C	-0.09 ± 0.04	-0.09 ± 0.04	-0.07 ± 0.04	-0.11 ± 0.05	-0.10 ± 0.04[A]	-0.09 ± 0.04[A,B]	

[A] Significantly (p<0.05) different from the narrow stance condition; [B] significantly different from the medium stance condition.

DISCUSSION: For the sagittal-plane NRJM, hip horizontal abduction increased with increasing width during the FO condition because of external rotations of the femur and tibia, accompanied by an alignment of the femur and tibia relative to its local mediolateral axis fixed to the thigh and shank segments. The alignment of the femur and tibia would also allow the hip to travel more posteriorly, which is accompanied by an increase in HEX (Fry et al., 2003). The cener-of pressure (COP) would then be shifted closer to the ankle. The alignment and the COP shift observed in the MS and WS conditions during the FO condition could lead to better squat performance with more hip and knee extensor muscles involved compared to the FF condition. In the NS and FO conditions, however, the hip was inhibited from traveling posteriorly due to external rotations of the femur and tibia causing the COP to be placed over a more anterior part of the feet, which would result in the significantly higher AP. The COP shift closer to the ankle joint with increasing width during the FO condition might cause AP to decrease and HEX to increase with the hip traveled more posteriorly. The trunk would also be more erect with increasing stance width during the FO condition due to increased hip horizontal abduction and hip external rotation which is accompanied by a decrease in trunk extensor moment (Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). The decreased AP and trunk extensor moment could be transferred to HEX and KEX.

For the frontal-plane NRJM, the COP was placed more on the lateral side of the feet with increasing stance width which resulted in the decrease in the moment arms from the joints to the line of action of the GRF vector in the frontal plane. This could cause smaller frontal-plane NRJM with increasing stance width. In addition, hip horizontal abduction increased when the femur and tibia became externally rotated and the COP was placed more on the lateral side of the feet during the FO condition, which could result in the change in the direction of the GRF vector more medially directed. A larger Q-angle (15.7° in females and 13.3° in males) observed in females might cause the GRF vector to be positioned outside the joints during the squat, which can decrease KAB for the female group.

CONCLUSION: It was concluded that various foot placements significantly affected the sagittal- and frontal-planes RJMs in the lower extremity joints during the squat. In order to provide people with a proper squat technique, therefore, it is important for practitioners and researchers to understand how the foot placement affects RJM in the lower extremity joints during the squat. Additionally, for more in-depth understanding of the squat the squat motion needs to be divided into more phases (AD, DD, AU, and DU) than two phases (up and down) due to the significant transition of the vertical COM acceleration in the middle of the downward and upward motions.

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