Journal of Exercise Science & Fitness 19 (2021) 269–277

Contents lists available at ScienceDirect

Journal of Exercise Science & Fitness

journal homepage: www.elsevier.com/locate/jesf

Relationships between physical characteristics and biomechanics of lower extremity during the squat

Sukbum Kim [a], Michael Miller [b], Ashley Tallarico [b], Sara Helder [b], Yuanlong Liu [b], Sangwoo Lee [b, *]

[a] *Department of Rehabilitation Personal Training, Konyang University, Nonsan-si, Chungcheongnam-do, South Korea*
[b] *Department of Human Performance and Health Education, Western Michigan University, Kalamazoo, MI, USA*

ARTICLE INFO

Article history:
Received 14 July 2021
Received in revised form
22 September 2021
Accepted 27 September 2021
Available online 4 October 2021

Keywords:
Resistance exercise
Joint flexibility
Motion analysis

ABSTRACT

Background/objective: There is a lack of information about relationship between physical characteristics and biomechanics of the lower extremity during the squat. Additionally, studies did not examine sex-related differences. The purpose of this study was to investigate relationships between physical characteristics and biomechanics of the lower extremity during the squat, and to determine if any sex differences are present.

Methods: Fifty three participants recruited (21.82 ± 2.3 years; 75.56 ± 14.98 kg; 171.57 ± 8.38 cm) performed three squats with 75% of one repetition maximum. Femur to tibia length ratio, hip and ankle joints' flexibilities, and relative muscular strength were measured and used as physical characteristics. Net joint torques (NJT) and flexion angles of the lower extremity were extracted as dependent variables. Multiple regression (stepwise) analysis was conducted to examine the relationships with physical characteristics being factors. Pearson correlation coefficients were calculated to determine intercorrelations among the dependent variables.

Results: Relative muscular strength was related to hip NJT and knee flexion angle, and hip flexibility was related to ankle dorsiflexion. Hip and knee NJT showed moderate correlations with the corresponding flexion angles ($r = 0.48\text{-}0.53$; $p < .01$). Ankle dorsiflexion angle showed weak to moderate correlations with hip NJT and hip flexion angle ($r = -0.36\text{-}0.50$; $p < .01$) and a moderate correlation with knee NJT. No significant sex difference was observed ($r = 0.52$; $p < .05$).

Conclusion: Biomechanics of the lower extremity has been shown to correlate more with relative muscular strength and joint flexibility than with leg length ratio.

1. Introduction

The squat is one of the most popular exercises in the field of strength and conditioning due to its wide range of applications. It is often included as a core exercise designed to improve athletic performance.[1,2] It is also an essential component of weightlifting as well as powerlifting competitions.[1] In the clinical setting, it is often used as a means to strengthen lower extremity muscles and connective tissues after joint-related injuries, such as anterior cruciate ligament injuries.[3,4] However, poor technique or improper exercise prescription can lead to conditions/injuries such as patellofemoral pain, menisci/articular cartilage injury, and spondylolysis.[5–11] Thus, several experimental factors during the squat have been investigated because of their potential influences on squat performance including foot placement,[1,12] speed,[13–15] style,[16] and bar position.[2]

It was reported that squat performance can also be related to individual's physical characteristics, such as leg length ratio and joint flexibility.[17,18] In terms of leg length ratio, a femur to tibia length ratio (FTR) needs to be treated especially important during the squat because the major movement of the squat involves flexion/extension of the hip and knee controlled by the movement of the femur and tibia. Demers et al.[17] assessed whether a change in the range of motion (ROM) of the lower extremity joints was affected by FTR during the squat and reported a greater FTR was

---

* Corresponding author. Department of Human Performance and Health Education, Western Michigan University, 1903 W. Michigan Avenue, Kalamazoo, MI, 49008, USA.

E-mail address: sangwoo.lee@wmich.edu (S. Lee).

https://doi.org/10.1016/j.jesf.2021.09.002

related to higher ankle dorsiflexion and knee flexion angles in a narrow squat stance. The flexibility of the lower extremity joints can show a strong relationship with ROM of the lower extremity during the squat.[18] Gomes et al.[18] examined a relationship between back squat depth and ankle flexibility and reported back squat depth was positively related to ankle dorsiflexion ROM.

Although the previous studies investigated the relationship between physical characteristics and biomechanics of the lower extremity during the squat,[17,18] there are still additional variables that can be addressed, such as relative muscular strength and sex-related differences.[19–21] Therefore, the purpose of this study was to investigate the relationships between physical characteristics and biomechanics of the lower extremity during the squat. Additionally, we sought to examine sex differences. We hypothesized that (1) physical characteristics including FTR, the flexibility of the hip and ankle, and relative muscular strength would be significantly related to net joint torque (NJT) and flexion angles of the lower extremity and (2) significant intercorrelations would be observed among the NJT and flexion angles of the lower extremity, and (3) there would be no significant differences in the variables between sexes.

2. Methods

2.1. Participants

Fifty three recreationally trained participants were recruited for this study (24 males and 29 females; 21.82 ± 2.3 years in age; 75.56 ± 14.98 kg in mass; 171.57 ± 8.38 cm in height) based on a priori G-power analysis with 3 predictors, a power of 0.80, an alpha level of 0.05, and a medium effect size of 0.23. The type of variable used was continuous, and the type of analysis performed was linear multiple regression. The inclusion and exclusion criteria for participant recruitment were as follows:

- o Inclusion: Individuals under the age of 18–30 and with at least two years of squatting experience. Individuals with a body mass index of lower than 30. Participants met all the inclusion criteria.
- o Exclusion: Individuals with musculoskeletal injuries within the past six months and with powerlifting experience. Participants with one or more exclusion criteria were excluded in this study.

This study was approved by the University Institutional Ethics Review Board. Before participating in the study, the participants were informed of the benefits and risks of the investigation prior to signing an informed consent document.

2.2. Procedures

On day one, the study was explained to the participants, and informed consent form was signed. Body mass, height, FTR, and ankle and hip flexibilities were then measured. For determining FTR, the femur was measured from the greater trochanter to the lateral femoral epicondyle, and the tibia was measured from the medial femoral epicondyle to the medial malleolus (Fig. 1a). A goniometer was used to measure flexibility of the hip and ankle. Measuring hip flexibility was taken at the greater trochanter along the midaxillary line of the participants. Hip reference angles were obtained initially with the participants in the supine position with their right leg lying flat on the table. The hip flexibility was then obtained by instructing the participants to lift their right leg while keeping their knee straight as far as possible (Fig. 1b). Measuring ankle flexibility was taken at the lateral malleolus along the length of the foot. Ankle reference angles were first obtained with the participants sitting on a table that allowed the ankle to have a natural position. The ankle flexibility was then measured by instructing the participants to perform dorsiflexion (Fig. 1c).

A one repetition maximum (1RM) squat test was conducted using the National Strength and Conditioning Association 1RM protocol.[22] The participants were asked to perform the full squat. To ensure safety, they were instructed to perform each repetition without the butt wink and trunk flexion and with the heels in contact with the floor. Relative muscular strength was quantified by dividing 1RM measured by body mass.[22]

On day two, the participants performed warm-up using the bike before engaging in the actual squat trials. They performed two-three warm-up squat trials, beginning with a bar of 20.4 kg for both men and women, and incrementally increasing the load until the weight of 75% of 1RM was reached. 10–20% of their 1RM was added to the bar with each set. Each participant completed three squat trials with the weight of 75% of 1RM as 75% of 1RM is recommended for improving hypertrophy in advanced lifters.[23] A rest period of two-three minutes between trials was allowed to minimize fatigue effect. Self-selected speed was used while foot placement was controlled to be pelvic-width apart as participants felt discomfort when the speed of movement was controlled. To ensure the reliability of the speed across trials, the range of the duration of the squat was measured.[24]

2.3. Experimental setup

Twenty five reflective markers were placed on anatomical landmarks for motion capture (Table 1 and Fig. 2), and one researcher was consistent in placing the markers. A 250-Hz six-camera Vicon motion capture system (Centennial, CO, USA) was used to capture the three-dimensional (3D) coordinates of the markers placed during the squat trials. All the markers placed were used to define joint centers and body segments. Two AMTI forceplates (Advanced Mechanical Technology, Inc., Watertown, MA, USA) were used to measure ground reaction forces (GRF). A T-pose was first recorded with all the markers to compute the locations of a group of secondary points. Medial landmarks including medial malleoli, medial femoral epicondyles, and anterior superior iliac spines (ASIS) were then removed. Participants oriented in the direction of the positive X-axis of the laboratory (i.e. global) reference frame. The positive Y-axis pointed leftward perpendicular to the X-axis. The positive Z-axis was vertically upward. The axes of the plates were aligned with those of the laboratory reference frame.

2.4. Data processing and analysis

Data were first processed using Vicon Nexus program to acquire C3D files. The C3D files processed were then imported into Kwon3D Motion Analysis Suite (Version XP; Visol Inc., Seoul, Korea) for subsequent data processing. The raw 3D coordinates of the markers were filtered using a Butterworth zero phase-lag fourth-order low-pass filter with a cut-off frequency of six Hz determined by using the residual method.[25] NJT and flexions of the lower extremity joints were selected as the dependent variables because both have been key variables in previous squat studies.[1,7,15,16]

The ASISs for dynamic trials were calculated using the rigid body method.[26] The hip joint center was located using the Tylkowski–Andriacchi hybrid method[27] and the joint between the fourth and fifth lumbar vertebrae (L4/5) was located using the MacKinnon method.[28] The knee and ankle joints centers were located using the mid-point of two markers (e.g. lateral and medial femoral epicondyle markers for the knee joint). Seven body segments (pelvis, thighs, shanks, and feet) were defined based on the captured makers for computing subsequent kinetic and kinematic data. Segmental reference frames were defined for the lower extremity segments (Table 1). The X-, Y-, and Z-axis of the segments were

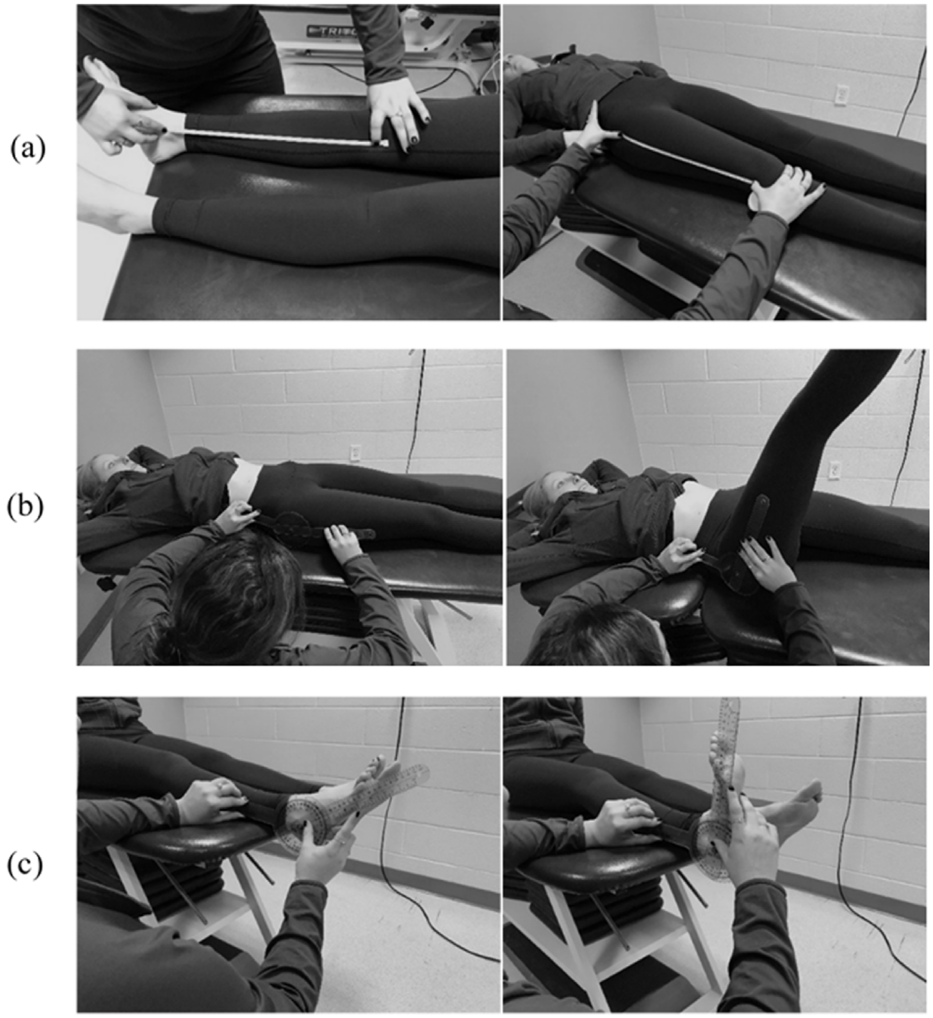

Fig. 1. Measurements of physical characteristics: (a) femur to tibia ratio, (b) hip flexibility, and (c) ankle flexibility.

aligned with the mediolateral, anteroposterior, and longitudinal axes of the segments, respectively. To define the segmental reference frames, an anatomical plane was first defined using two axes (first axis and temporary second axis). The third axis was then defined by using the cross product of the first and temporary second axes' unit vectors. The true second axis was lastly determined by using the cross product of the first and third axes' unit vectors.

For computing the flexion angles of the lower extremity joints, the orientations matrices of the lower extremity segments were first established from the axis unit vectors of the segmental reference frames.[29] The relative orientations matrices of the segments to their linked proximal segments were then built from the orientation matrices. The flexion angles of the lower extremity were calculated as the relative orientation angle of a distal segment to its proximal segment using the Cardan sequence of XYZ (mediolateral-anteroposterior-longitudinal). The first orientation angle about the mediolateral axis was used as the flexion angle (Fig. 3).

The body segment parameters measured by de Leva[30] were employed in calculating the center-of-mass (CM), mass, and principal moment-of-inertia of the segments. The Joint Coordinate System (JSC) convention proposed by Grood and Suntay[31] was applied in extracting NJT. The JCS states that the first rotation is fixed to the proximal segment, the second rotation is around a floating axis that is shared between the proximal and distal segments, and lastly the third rotation is fixed to the distal segment. NJT in the sagittal plane were extracted for data analysis (Fig. 3) and the computed NJT were normalized to total (body + barbell) mass. NJT acting on hip, knee, and ankle joints were calculated using an inverse dynamics procedure:[32]

$$\mathrm{NJT} = \sum_{s=1}^{n}\left(\frac{d\boldsymbol{L}_s}{dt} + r_s \times \frac{d\boldsymbol{P}_s}{dt}\right) - \sum_{s=1}^{n}(r_s \times W_s) - \left(r_{grf} \times F_{grf} + T_z\right)$$

where s is the segment, n is the number of segments, $\frac{d\boldsymbol{L}_s}{dt}$ is the time-derivative of the local angular momentum of each segment that is due to the rotation of the segment about its CM, r_s is the position vector drawn from a joint center to each segment's CM, $\frac{d\boldsymbol{P}_s}{dt}$ is the time-derivative of the linear momentum of each segment, $r_s \times \frac{d\boldsymbol{P}_s}{dt}$ is the torque produced due to the rotation of a segment about the joint, W_s is the weight of each segment, $r_s \times W_s$ is the torque produced due to the weight of each segment, r_{grf} is the position vector drawn from a joint center to the center-of-pressure (CP), F_{grf} is the GRF vector, $r_{grf} \times F_{grf}$ is the torque produced due to GRF, and T_z is the twisting torque acting at the CP.

2.5. *Statistical analysis*

To ensure the consistency of a squat speed across trials, the

Table 1
Markers placed and definitions of segment reference frames of each segment.

Segment	Markers	Axes	Anatomical plane	Linked proximal segment
Pelvis	Right and left anterior superior iliac spines (ASIS), right and left posterior superior iliac spines, sacrum, and right and left iliac crests.	Left ASIS marker to right ASIS marker (+X axis) Sacrum marker to mid-ASIS point (+Y axis)	Transverse	Global
Right Thigh	Right greater trochanter, lateral thigh, and lateral and medial epicondyles	Knee joint to hip joint (+Z axis) Hip joint to lateral thigh marker (+X axis)	Frontal	Pelvis
Left Thigh	Left greater trochanter, lateral thigh, and lateral and medial epicondyles	Knee joint to hip joint (+Z axis) Hip joint to lateral thigh marker (-X axis)	Frontal	Pelvis
Right Shank	Right lateral shank and lateral and medial malleoli	Ankle joint to knee joint (+Z axis) Knee joint to lateral shank marker (+X axis)	Frontal	Right thigh
Left Shank	Left lateral shank and lateral and medial malleoli	Ankle joint to knee joint (+Z axis) Knee joint to lateral shank marker (-X axis)	Frontal	Left thigh
Right Foot	Right toe and heel	Toe marker to heel marker (+Z axis) Heel marker to ankle joint (+Y axis)	Sagittal	Right shank
Left Foot	Left toe and heel	Toe marker to heel marker (+Z axis) Heel marker to ankle joint (+Y axis)	Sagittal	Left shank

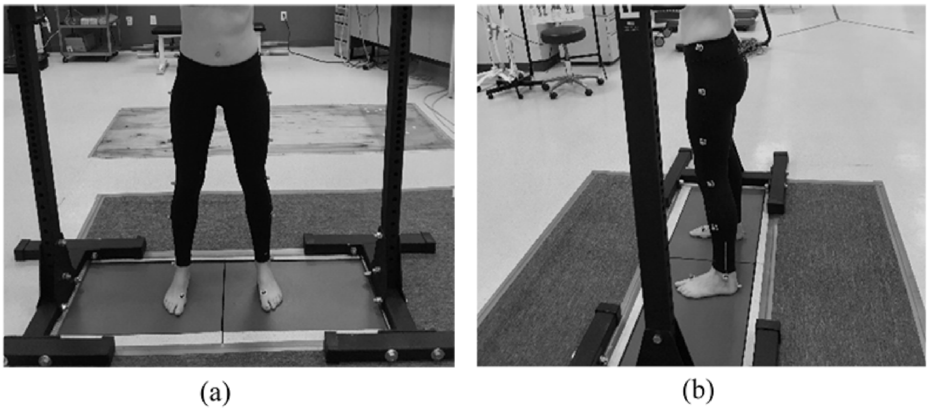
(a) (b)

Fig. 2. Frontal (a) and Sagittal (b) views of marker placement.

reliability of the speed was assessed using intraclass correlation coefficients (ICC) for the durations of descending, ascending, and total movements. The averaged peak values of the NJT and flexion angles of the lower extremity were used for statistical analysis.

Multiple regression (stepwise) analysis was conducted to determine the best combination of the physical characteristics for each dependent variable with both sexes combined and sex by sex. The results of multiple regression analysis were used to explain the hypothesis that physical characteristics would be significantly related to NJT and flexion angles of the lower extremity. Independent variables were FTR, joint flexibility of the hip and ankle, and relative muscular strength, and dependent variables were the lower extremity NJT and flexion angles. The level of significance was set at .05. Cohen's $f^2$was used as a measure of effect size (ES) for the multiple regression. The ranges of $0.02 \leq f^2 < 0.15$, $0.15 \leq f^2 < 0.35$, $f^2 \geq 0.35$ were considered to be small, medium, and large, respectively.

Pearson correlation coefficients were also obtained to observe relationships among the dependent variables with both sexes combined and sex by sex. The results of correlation were used to explain the hypothesis that significant intercorrelations would be observed among the NJT and flexion angles of the lower extremity. The ranges of $0.2 \leq |r| < 0.4$, $0.4 \leq |r| < 0.6$, and $0.6 \leq |r| < 1$ were defined as weak, moderate, and strong correlations, respectively. The Bonferroni corrected p values were applied to the multiple correlations for controlling family-wise error rate (i.e. the inflation of the critical p value as a result of increasing the number of comparisons). The IBM SPSS Statistics version 24 (IBM, New York) was used for all statistical tests.

3. Results

The mean FTR, joint flexibility of the hip and ankle, and relative muscular strength were 1.08 ± 0.08, 84.52 ± 13.57°, 11.22 ± 6.66°, and 1.39 ± 0.36, respectively. The results of the ICC measured to assess the reliability of speed were 0.95 for the descending duration, 0.96 for the ascending duration, and 0.96 for the total movement duration, respectively.

When both sexes were combined, relative muscular strength was significantly related to hip NJT with 14.5% of the variance explained and knee flexion angle with 29.1% of the variance explained (Fig. 4). Hip flexibility was significantly related to ankle dorsiflexion with 10.7% of variance explained. However, FTR was not significantly related to NJT and flexion angles of the lower extremity. The male group showed hip flexibility was significantly related to ankle dorsiflexion with 47.6% of variance explained, which was consistent with the result when both sexes were combined, while there was no significant relationship observed in the

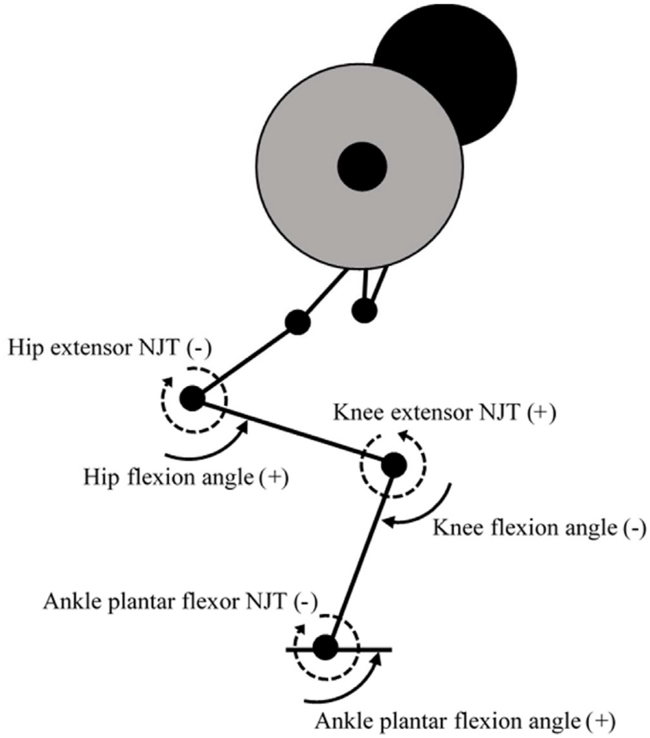

Fig. 3. The biomechanical variables extracted during the squat. The clockwise and counter clockwise directions were defined as negative and positive, respectively.

female group. Significant correlations were observed among the dependent variables (Table 2). When both sexes were combined, hip and knee NJT were positively related to the corresponding flexion angle ($r = 0.48$ - 0.53) which were moderate associations. Ankle dorsiflexion angle was negatively related to hip NJT ($r = -0.36$, weak association) and hip flexion angle ($r = -0.50$, moderate association) while it was positively related to knee NJT ($r = 0.52$, moderate association). Male and female groups also showed similar correlation results to those when both sexes were combined.

The means of the hip, knee, and ankle NJT were 1.16 ± 0.23 $\text{Nm}\cdot\text{kg}^{-1}$, 0.78 ± 0.17 $\text{Nm}\cdot\text{kg}^{-1}$, and 0.43 ± 0.15 $\text{Nm}\cdot\text{kg}^{-1}$, respectively. NJT of the lower body joints increased as the participants squatted down and decreased as they came back up the initial upright position (Fig. 5).

4. Discussion

This study investigated relationships between physical characteristics and biomechanics of the lower extremity during the squat. FTR, hip and ankle flexibility, and muscular strength were selected as the physical characteristics due to their potential effects. To our knowledge, this was the first study examining the above-mentioned relationships, and the findings of the current study are expected to provide more insightful understanding of biomechanics during the squat.

The key finding of this study was that participants with increased relative muscular strength had greater hip NJT and knee flexion during the squat when both sexes were combined. Participants with greater relative muscular strength seem to rely more on the hip flexor to lift heavier weight and have greater knee flexion while squatting. Participants with increased relative muscular strength tend to promote greater hip muscle use from the deeper squat in order to extend the knees during the upward phase. The effect sizes between relative muscular strength and hip NJT and between relative muscular strength and knee flexion were medium (0.16) and large (0.41), respectively.

It was also observed that as the participants squatted, NJT of the lower body increased, and it maximized at the bottom of the squat (Fig. 5). Therefore, based on the positive relationship between relative muscular strength and hip NJT and knee flexion angle, and the NJT results, participants with greater muscular strength show greater muscle use in the lower limbs, attributable to increased squat depth. No comparable data on the correlation of relative muscular strength and hip NJT and knee flexion during the squat exists; however, Andersen et al.[19] reported that relative muscular strength of the lower body showed a significant positive correlation with vertical jump in collegiate women soccer players. The positive correlation is likely due to the fact that athletes with greater muscular strength utilized lower body muscles to jump higher by squatting deeper, which is consistent with our findings. However, the previous study exhibited that developing greater strength can degrade other areas of training, such as speed and agility. Therefore, it should be noted that it is important to build the optimal level of strength to be successful in sports, not just to be stronger.

Our results also showed that when both sexes were combined, an increase in hip flexibility was related to a decrease in ankle dorsiflexion. It is likely that participants with greater hip flexibility use hip extensors when squatting deeper, causing the ankle to be less dorsiflexed. This explanation is supported by our results, which showed that hip NJT was negatively related to ankle dorsiflexion angle (Table 2). However, since the correlation between hip NJT and ankle dorsiflexion angle was weak ($r = -0.36$), this relationship needs to be carefully interpreted. It should also be noted that greater hip flexion resulting in the increased use of the hip extensors is accompanied by greater forward lean of the trunk resulting in the increase in shear force on the spine.[7] Therefore, the trunk needs to remain as upright as possible during the squat to minimize the loads on the spine.

The results of intercorrelation among the dependent variables indicated that when both sexes were combined, hip and knee NJT were positively related to the corresponding joint flexion angles (Table 2). Thus, an increase in hip NJT and knee flexion correlated with increased muscular strength would increase hip flexion and knee NJT, respectively although our regression results did not A negative correlation was found between hip flexion and ankle dorsiflexion angles, indicating that greater hip flexion caused the shank to become more vertical during the squat. These results were not fully supported by the fact that the squat is considered as a closed chain exercise in which a movement in a one joint simultaneously generates movements in other joints of the extremity in a predictable manner.[4] These results were also inconsistent with the previous study indicating back squat depth was positively related to ankle dorsiflexion ROM measured using a smartphone digital goniometer during a lunge test.[18] However, it should be noted that we measured ankle dorsiflexion in the squat while it was measured during the lunge in the previous study, and the two exercises differ from each other in terms of their posture.

There has been anecdotal evidence among coaches and practitioners that different leg length ratios can change biomechanics of the lower extremity during the squat. We found the lower extremity biomechanics correlated more with relative muscular strength and joint flexibility than with leg length ratio. Our results, however, were not supported by previous research showing a greater FTR was positively related to higher ankle dorsiflexion and knee flexion angles.[17] The inconsistency may be attributable to a discrepancy in stance width between the studies. A single stance with pelvic-width apart was used in our study while various stances (i.e. narrow, medium, and wide) were used in the previous

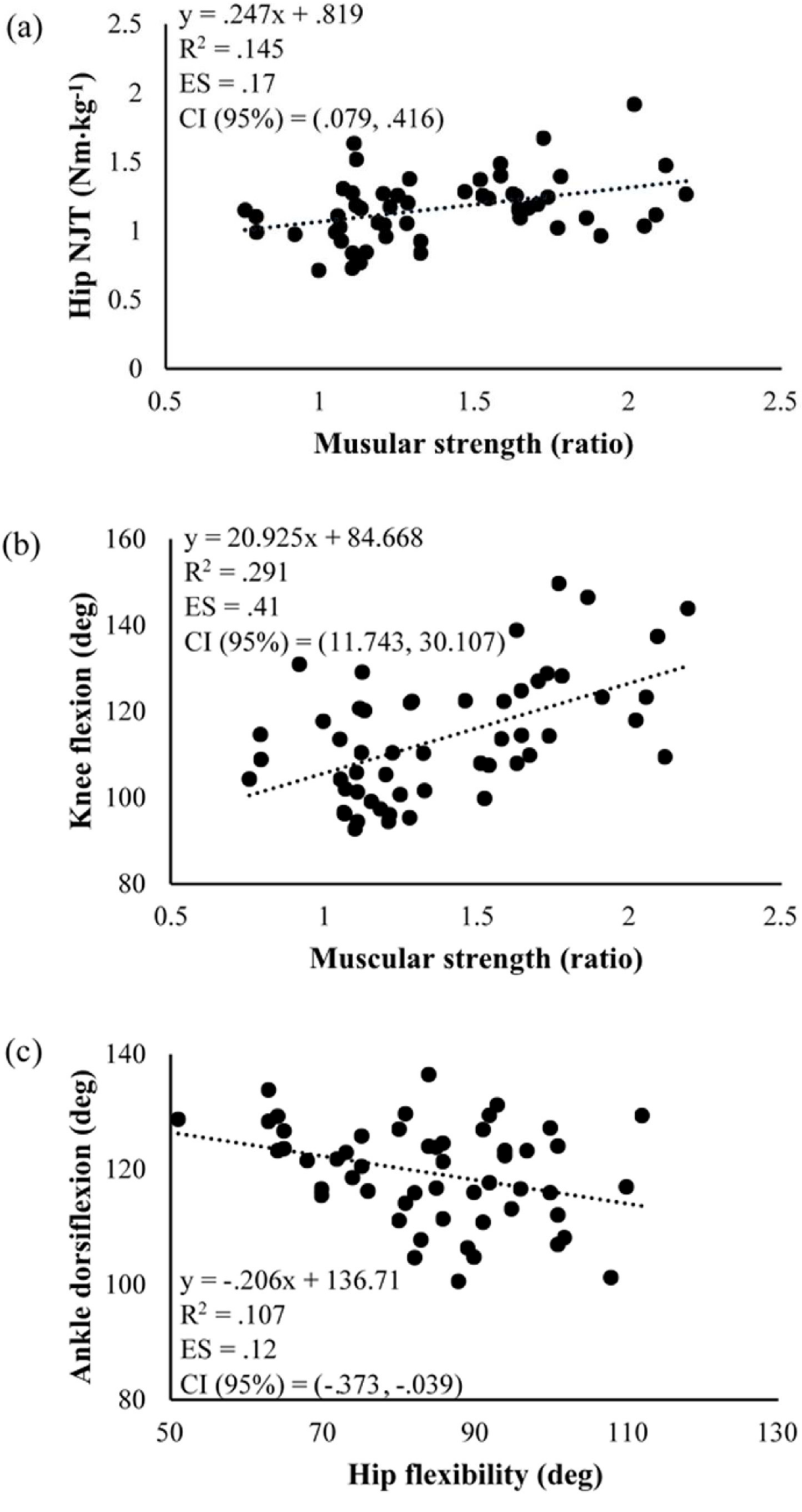

Fig. 4. Scatter plots of the significant dependent variables versus physical characteristics when both sexes were combined: (a) hip net joint torque (NJT)-muscular strength, (b) knee flexion angle-muscular strength, and (c) ankle dorsiflexion angle-hip flexibility. ES and CI represent the effect size and confidence intervals, respectively.

Table 2
Results of the intercorrelation among the dependent variables.

Group		1	2	3	4	5	6
Combined	1. Hip NJT	–					
	2. Knee NJT	-.04	–				
	3. Ankle NJT	.13	.13	–			
	4. Hip flex.	**.53****	-.18	.11	–		
	5. Knee flex.	.17	**.48****	.16	.12	–	
	6. Ankle flex.	**-.36****	**.52****	.35*	**-.5****	.33*	–
Male	1. Hip NJT	–					
	2. Knee NJT	.02	–				
	3. Ankle NJT	.01	.28	–			
	4. Hip flex.	**.60****	-.31	-.10	–		
	5. Knee flex.	-.22	**.61****	.06	-.01	–	
	6. Ankle flex.	-.40	**.64****	.30	**-.61****	.44*	–
Female	1. Hip NJT	–					
	2. Knee NJT	-.22	–				
	3. Ankle NJT	.20	.01	–			
	4. Hip flex.	**.50****	-.09	.26	–		
	5. Knee flex.	.43	**.47***	.29	.16	–	
	6. Ankle flex.	-.38*	.40*	.41*	-.43*	.42*	–

Note. *$p < .05$, **$p < .01$. Bold indicates correlation is significant at alpha level corrected by the Bonferroni method.

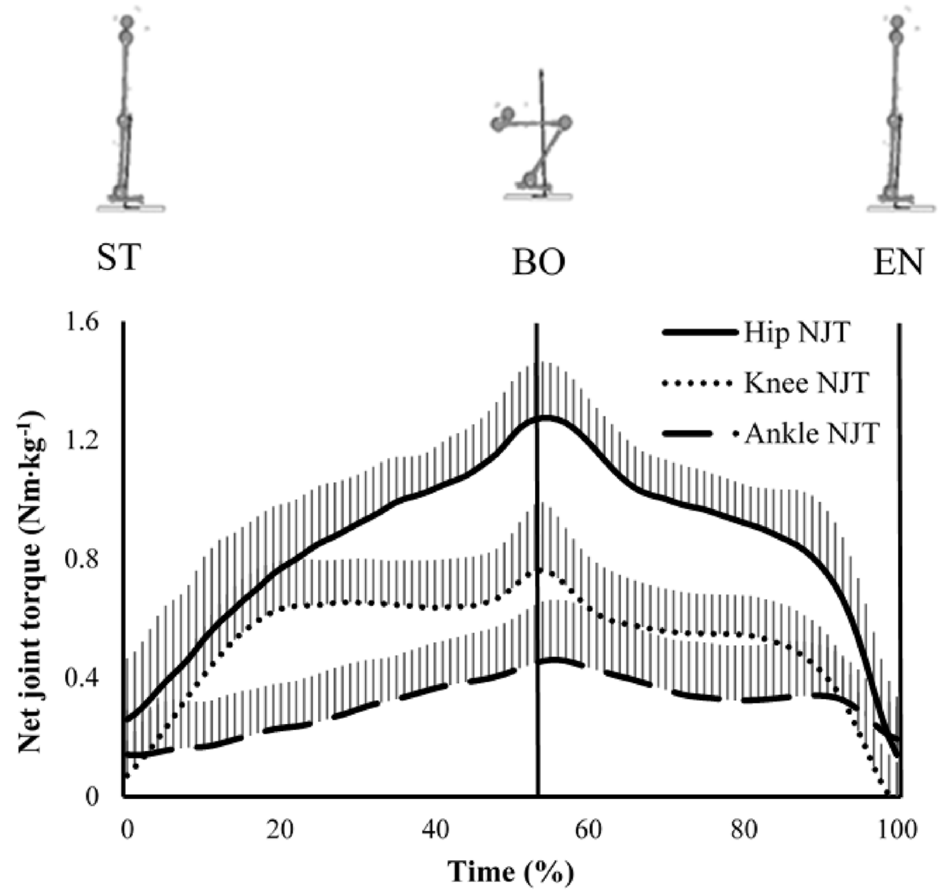

Fig. 5. The ensemble-averaged graphs of the net joint torques (NJT) of the lower extremity in relation to the squat events. The negative values of the hip and ankle NJT were flipped into positive ones. ST, BO, and EN represented Start of Squat, Bottom of Squat, and End of Squat, respectively.

study. Moreover, the methodological discrepancy in the load of the squat between the previous (unloaded back squat) and current (75% of 1RM) studies could lead to the inconsistency.

Our study conducted separate multiple regression and correlation analyses of male and female groups as well as both sexes combined to identify whether any sex-induced heterogeneity existed and whether the results of both sexes combined differed from those of male and female groups. The male and female groups exhibited the same regression results except the fact that the male group showed hip flexibility was significantly related to ankle dorsiflexion while there was no significant relationship observed in the female group. Males with greater hip flexibility can use more hip extensors by squatting deeper as opposed to females, which can lead to decreased ankle dorsiflexion in males. Also, intercorrelations among the dependent variables showed similar results between the male and female groups, which were in line with the results of both sexes combined. Although there was no significant sex difference in this study, it should be noted that a multidisciplinary approach involving inherent and modifiable factors needs to be considered when it comes to sex comparison for improving validity and avoiding hasty generalization[33] because sex-related differences were observed in various sports.[19–21]

Despite the novelty of our study, there were limitations. First, 75% of 1RM is a lower percentage compared to 1RM, and form is likely to change when the intensity increases. Second, despite the potential bilateral asymmetry between the legs, only one side of the legs (i.e. right leg) were analyzed in this study. Third, since participants performed the squat under controlled experimental conditions, there would be issues related to the implication of lab results to the real life. Nevertheless, the findings of this study are expected to enable us to generally understand how physical characteristics are related to biomechanics of the lower extremity joints during the squat. Lastly, recreationally trained individuals with at least two to three years of squat experience were recruited, thus, the results may need to be cautiously generalized to those with different levels of fitness.

5. Conclusion

Our study reveals that physical characteristics are significantly related to biomechanics of the lower extremity during the squat; however, no sex differences are present. Specifically, NJT and flexion angles of the lower extremity during the squat have been shown to correlate more with relative muscular strength and joint flexibility than with leg length ratio.

Practically, when coaches and practitioners deal with their athletes and patients to execute the squat in exercise and rehabilitation programs, they are encouraged to design the programs in light of each individual's muscular strength and joint flexibility. The dependence of the hip and the squat depth become greater as lifters improve strength. Also, the hip flexibility is related to the dorsiflexion of the ankle. Thus, coaches and practitioners can consider including exercises, such as the good morning or hip thrust, specifically for strengthening hip extensors to secure both safety and effectiveness during the squat. Besides that, individuals are recommended to practice a full squat with light to heavy weights to improve joint flexibility.

Two recommendations are warranted for future research. First, the relationship between physical characteristics and lower extremity biomechanics during the squat needs to be scrutinized at maximum or sub-maximal weight. Second, the reliability of joint kinetics and kinetics between the legs during the squat needs to be examined.

Declaration of competing interest

The authors have no conflicts of interest to declare.

Acknowledgements

This study was supported by Western Michigan University in Kalamazoo, Michigan, United States.

References

1. Escamilla RF, Fleisig GS, Lowry TM, Barrentine SW, Andrews JR. A three-dimensional biomechanical analysis of the squat during varying stance widths. *Med Sci Sports Exerc*. 2001;33(6):984–998. https://doi.org/10.1097/00005768-200106000-00019.
2. Schoenfeld BJ. Squatting kinematics and kinetics and their application to exercise performance. *J Strength Condit Res*. 2010;24(12):3497–3506. https://doi.org/10.1519/JSC.0b013e3181bac2d7.
3. Stuart MJ, Meglan DA, Lutz GE, Growney ES, An KN. Comparison of intersegmental tibiofemoral joint forces and muscle activity during various closed kinetic chain exercises. *Am J Sports Med*. 1996;24(6):792–799. https://doi.org/10.1177/036354659602400615.
4. Tagesson S, Oberg B, Good L, Kvist J. A comprehensive rehabilitation program with quadriceps strengthening in closed versus open kinetic chain exercise in patients with anterior cruciate ligament deficiency: a randomized clinical trial evaluating dynamic tibial translation and muscle function. *Am J Sports Med*. 2008;36(2):298–307. https://doi.org/10.1177/0363546507307867.
5. Cappozzo A, Felici F, Figura F, Gazzani F. Lumbar spine loading during half-squat exercises. *Med Sci Sports Exerc*. 1985;17(5):613–620.
6. Escamilla RF. Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc*. 2001;33(1):127–141. https://doi.org/10.1097/00005768-200101000-00020.
7. Fry AC, Smith JC, Schilling BK. Effect of knee position on hip and knee torques during the barbell squat. *J Strength Condit Res*. 2003;17(4):629–633. https://doi.org/10.1519/1533-4287(2003)017<0629:eokpoh>2.0.co;2.
8. Miller JP, Sedory D, Croce RV. Leg rotation and vastus medialis oblique/vastus lateralis electromyogram activity ratio during closed chain kinetic exercises prescribed for patellofemoral pain. *J Athl Train*. 1997;32(3):216–220.
9. Vakos JP, Nitz AJ, Threlkeld AJ, Shapiro R, Horn T. Electromyographic activity of selected trunk and hip muscles during a squat lift. Effect of varying the lumbar posture. *Spine*. 1994;19(6):687–695. https://doi.org/10.1097/00007632-199403001-00008.
10. Yack HJ, Collins CE, Whieldon TJ. Comparison of closed and open kinetic chain exercise in the anterior cruciate ligament-deficient knee. *Am J Sports Med*. 1993;21(1):49–54. https://doi.org/10.1177/036354659302100109.
11. Comfort P, McMahon JJ, Suchomel TJ. Optimizing squat technique-revisited. *Strength Condit J*. 2018;40(6):68–74. https://doi.org/10.1519/SSC.0000000000000398.
12. Almosnino S, Kingston D, Graham RB. Three-dimensional knee joint moments during performance of the bodyweight squat: effects of stance width and foot rotation. *J Appl Biomech*. 2013;29(1):33–43. https://doi.org/10.1123/jab.29.1.33.
13. Bentley JR, Amonette WE, De Witt JK, Hagan RD. Effects of different lifting cadences on ground reaction forces during the squat exercise. *J Strength Condit Res*. 2010;24(5):1414–1420. https://doi.org/10.1519/JSC.0b013e3181cb27e7.
14. Hatfield DL, Kraemer WJ, Spiering BA, et al. The impact of velocity of movement on performance factors in resistance exercise. *J Strength Condit Res*. 2006;20(4): 760–766. https://doi.org/10.1519/R-155552.1.
15. Morrissey MC, Harman EA, Frykman PN, Han KH. Early phase differential effects of slow and fast barbell squat training. *Am J Sports Med*. 1998;26(2): 221–230. https://doi.org/10.1177/03635465980260021101.
16. Swinton PA, Lloyd R, Keogh JW, Agouris I, Stewart AD. A biomechanical comparison of the traditional squat, powerlifting squat, and box squat. *J Strength Condit Res*. 2012;26(7):1805–1816. https://doi.org/10.1519/JSC.0b013e3182577067.
17. Demers E, Pendenza J, Radevich V, Preuss R. The effect of stance width and anthropometrics on joint range of motion in the lower extremities during a back squat. *Int J Exerc Sci*. 2018;11(1):764–775.
18. Gomes J, Neto T, Vaz JR, Schoenfeld BJ, Freitas SR. Is there a relationship between back squat depth, ankle flexibility, and Achilles tendon stiffness? [published online ahead of print, 2020 Feb 5] *Sports BioMech*. 2020:1–14. https://doi.org/10.1080/14763141.2019.1690569.
19. Andersen E, Lockie RG, Dawes JJ. Relationship of absolute and relative lower-body strength to predictors of athletic performance in collegiate women soccer players. *Sports*. 2018;6(4):106. https://doi.org/10.3390/sports6040106.
20. Nimphius S, McBride JM, Rice PE, Goodman-Capps CL, Capps CR. Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *J Sports Sci Med*. 2019;18(1):101–108.
21. Huebner M, Perperoglou A. Sex differences and impact of body mass on performance from childhood to senior athletes in Olympic weightlifting. *PLoS One*. 2020;15(9), e0238369. https://doi.org/10.1371/journal.pone.0238369.
22. Ryan ED, Cramer JT. Fitness testing protocols and norms. In: Coburn JW, Malek MH, eds. *NSCA's Essentials of Personal Training*. Champaign, IL: Human Kinetics; 2012:201–247.
23. Haff GG, Haff EE. Resistance training program design. In: Coburn JW, Malek MH, eds. *NSCA's Essentials of Personal Training*. Champaign, IL: Human Kinetics; 2012:347–388.
24. Lee S, Schultz JR, Timgren JD, Staelgraeve KM, Miller MG, Liu Y. An electromyographic and kinetic comparison of conventional and Romanian deadlifts. *J Exerc Sci Fit*. 2018;16(3):87–93.
25. Winter DA. In: *Biomechanics and Motor Control of Human Movement*. fourth ed. Hoboken, NJ: Wiley; 2009.
26. Kwon YH, Como CS, Singhal K, Lee S, Han KH. Assessment of planarity of the golf swing based on the functional swing plane of the clubhead and motion planes of the body points. *Sports BioMech*. 2012;11(2):127–148. https://doi.org/10.1080/14763141.2012.660799.
27. Bell AL, Pedersen DR, Brand RA. A comparison of the accuracy of several hip center location prediction methods. *J Biomech*. 1990;23(6):617–621. https://

doi.org/10.1016/0021-9290(90)90054-7.

28. MacKinnon CD, Winter DA. Control of whole body balance in the frontal plane during human walking. *J Biomech*. 1993;26(6):633–644. https://doi.org/10.1016/0021-9290(93)90027-c.
29. Kwon YH. Measurement for deriving kinematic parameters: numerical methods. In: Hong Y, Bartlett R, eds. *Routledge Handbook of Biomechanics and Human Movement Science*. Abingdon-on-Thames, Oxfordshire: Routledge; 2008:156–181.
30. de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. *J Biomech*. 1996;29(9):1223–1230. https://doi.org/10.1016/0021-9290(95)00178-6.
31. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J Biomech Eng*. 1983;105(2):136–144. https://doi.org/10.1115/1.3138397.
32. Levine NA, Hasan MB, Avalos MA, Lee S, Rigby BR, Kwon YH. Effects of kettlebell mass on lower-body joint kinetics during a kettlebell swing exercise [published online ahead of print, 2020 Mar 4]. *Sports BioMech*. 2020:1–14. https://doi.org/10.1080/14763141.2020.1726442.
33. Nimphius S. Exercise and sport science failing by design in understanding female athletes [published online ahead of print, 2019 sep 25]. *Int J Sports Physiol Perform*. 2019:1–2. https://doi.org/10.1123/ijspp.2019-0703.