2-2022

Muscle-Specific Contributions to Lower Extremity Net Joint Moments While Squatting With Different External Loads

Kristof Kipp
Marquette University, kristof.kipp@marquette.edu

Hoon Kim
Marquette University

William I. Wolf
University of Puget Sound

Journal of Strength and Conditioning Research, Vol. 36, No. 2 (February 2022): 324-331. DOI.

Muscle-Specific Contributions to Lower Extremity Net Joint Moments While Squatting with Different External Loads

Kristof Kipp
Department of Physical Therapy, Program in Exercise Science, Marquette University, Milwaukee, Wisconsin
Hoon Kim
Department of Physical Therapy, Program in Exercise Science, Marquette University, Milwaukee, Wisconsin
William I. Wolf
School of Physical Therapy, University of Puget Sound, Tacoma, Washington

Abstract

The purpose of this study was to determine muscle-specific contributions to lower extremity net joint moments (NJMs) during squats with different external loads. Nine healthy subjects performed sets of the back squat exercise with 0, 25, 50, and 75% of body mass as an added external load. Motion capture and force plate data were used to calculate NJMs and to estimate individual muscle forces via static optimization. Individual muscle forces were multiplied by their respective moment arms to calculate the resulting muscle-specific joint moment. Statistical parametric mapping ($\alpha = 0.05$) was used to determine load-dependent changes in the time series data of NJMs and muscle-specific joint moments. Hip, knee, and ankle NJMs all increased across each load condition. The joint extension moments created by the gluteus maximus and hamstring muscles at the hip, by the vastii muscles at the knee, and by the soleus at the ankle all increased across most load conditions. Concomitantly, the flexion moment created by the hamstring muscles at the knee also increased across most load conditions. However, the ratio between joint moments created by the vastii and hamstring muscles at the knee did not change across load. Similarly, the ratio between joint moments created by the gluteus maximus and hamstring muscles at the hip did not change across load. Collectively, the results highlight how individual muscles contribute to NJMs, identify which muscles contribute to load-dependent increases in NJMs, and suggest that joint moment production among synergistic and antagonistic muscles remains constant as external load increases.

Introduction

Resistance training exercises form the foundation of many strength and conditioning programs because proper application can elicit desirable increases in neuromuscular structure and function, such as muscle size and strength [8,14,22]. The adaptations that are observed in response to resistance training programs are stimulus specific and depend on the demands imposed on the neuromuscular system during individual training sessions [8,10]. Given that many of the most common and effective resistance training exercises involve the coordinated actions of many muscles (e.g., as in the back squat), optimal implementation of these exercises requires an understanding of the mechanical demands that are imposed on individual muscles or muscle groups during their execution.

A common way for researchers to estimate the mechanical demands of resistance training exercises is through the calculation of the net internal (or muscle) joint moments (NJMs) via the inverse dynamics approach [7,12,23]. The examination of NJMs provides information about the net effect or effort of all active (i.e., force-producing) and passive (e.g., ligamentous) structures that act about the respective joint and is purported to offer insight into the neuromuscular demands imposed by multijoint resistance training exercises [4]. For example, multiple authors have investigated the effects of external load on lower extremity NJMs during the back squat, front squat, and deadlift and found that increases in load led to increases in NJMs at most of the lower extremity joints [5,7,15]. Although this information has provided critical information for the effective application of resistance training exercises, the information obtained from the inverse dynamics approach is subject to several limitations.

The most important limitation associated with the inverse dynamics approach is that NJMs only provide information about the net effect of all muscles that act across the respective joints under investigation [4,25]. Given that groups of antagonistic muscles, such as the quadriceps and hamstrings, could cocontract in any possible number of combinations, it is not possible to determine whether an increase in NJMs is the result of greater agonist contraction or a greater (yet balanced) agonist and antagonist contraction [4]. It is therefore likely that NJMs underestimate the mechanical demands imposed on agonist muscles [2]. Furthermore, in the case in which multiple muscles act synergistically to create flexion or extension moments about a joint, it is not possible to ascertain a muscle's individual contributions based on the respective NJMs. The presence of mono- and bi-articular muscles further complicates determining individual contributions and interpreting NJMs.

One approach to overcoming the limitations associated with the calculation and interpretation of NJMs is to use musculoskeletal and computational models to estimate the activation of individual muscles during resistance training exercises [13,24]. Given that these models can account for musculoskeletal geometry (e.g., internal moment arms) and force-length-velocity properties of individual muscles, which are neglected by electromyography (EMG)-based models, they can provide novel insights into important applied problems [6,9]. Importantly, the internal moment arm and muscle force data from these models can be combined to determine the contribution of individual muscles to NJMs, regardless of whether a muscle acts as an agonist, antagonist, or synergist during a resistance training exercise [16]. The purpose of this study was to determine muscle-specific contributions to lower extremity NJMs in the sagittal plane during squats with different external loads. We hypothesized that NJMs would increase with load and that this increase would be driven by a certain set of muscles. The goal of this research is to expand on the limited information about the neuromuscular demands during the execution of multijoint resistance training exercises.

Methods

Experimental Approach to the Problem

To determine the effect of load on muscle-specific contributions to lower extremity NJMs in the sagittal plane, subjects performed squats with 4 different external loads while motion capture, and force plate data were recorded. The internal NJMs were calculated via inverse dynamics, and individual muscle forces were estimated via static optimization. Individual muscle forces were multiplied with their respective moment arms to calculate the resulting muscle-specific joint moments, which were compared with statistical parametric mapping (SPM) to determine load-dependent changes throughout the entire squat motion.

Subjects

Nine male NCAA Division I track and field athletes (age: 21.8 ± 0.1 years [range 19–22]; height: 1.82 ± 0.06 m; body mass: 81.5 ± 6.3 kg; 1 repetition maximum back squat: 161 ± 15 kg; ± *SD*) participated in this study. All subjects were experienced with the back squat exercise, were healthy, and did not report any cardiovascular or musculoskeletal problems that would have compromised their ability to safely participate in the current study. All subjects were briefed on the purpose of the study and gave written informed consent before their participation. The study was approved by the Institutional Review Board for Human Subject Testing at Marquette University.

Procedures

Twenty-nine reflective markers were attached over distinct anatomical landmarks of each subject who subsequently performed a brief warm-up that consisted of calisthenic (e.g., squats and lunges) and stretching (e.g., quadriceps and hamstring stretches) exercises [13]. For the back squat, subjects could perform the exercise with their preferred technique and squat depth (Figure 1). During the execution of the back squat, subjects were asked to position each foot on one of the force plates and execute each repetition to the sound of a metronome set to 0.5 Hz (i.e., 2-second eccentric and concentric phase). Because the speed of movement would affect the force-velocity behavior of the respective muscles, the metronome was used to ensure that movement speed would not confound the effect of load. After a brief familiarization with the foot placement and the movement speed, each subject executed 3 repetitions with 4 additional external loads: 0, 25, 50, and 75% of body mass (BM). The order of execution was not randomized to allow for safe progression from low to high loads. Subjects executed the 0% condition with a wooden dowel on their shoulders to simulate the same positioning as with a weightlifting bar. Subjects executed all other conditions with a weightlifting bar (20 kg) and bumper plates.

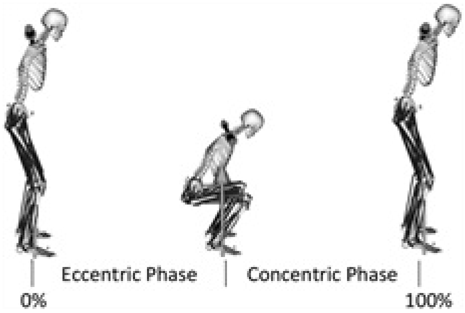


Figure 1.: Illustration of the beginning, middle, and end of the back squat exercise.

During the execution of each repetition of the back squat, ground reaction forces (GRFs) were collected at 1,000 Hz with 2 force plates (Models OR6-6, Advanced Mechanical Technologies Inc., Watertown, MA), and positions of reflective markers were recorded at 100 Hz with 14 motion capture cameras (T-Series Cameras, Vicon Denver, Centennial, CO). All data were recorded and synchronized in Nexus 1.8.5 (Vicon Denver).

Data Analysis

All data were filtered with a fourth-order low-pass Butterworth filter at cutoff frequencies of 12 Hz. The filtered GRF and marker position data were used as inputs to a musculoskeletal model in OpenSim v3.3 [6], which was specifically created for tasks with large hip and knee joint flexion motions [3]. The model parameters were scaled to each subject's anthropometric data (e.g., segment lengths) derived from a static trial (Figure 2). For back squats with loads greater than 0%, a weightlifting bar was attached to the torso segment (around seventh cervical vertebrae) and modeled as a point mass. The joint angles were calculated by minimizing the squared distance between each subject's markers during the dynamic motion and the markers of the model via inverse kinematics [11]. The internal NJMs were calculated via inverse dynamics. Dynamically consistent kinematics between the musculoskeletal model and the motion of the markers during the experimental conditions were obtained through minimization of residuals with a residual reduction algorithm (RRA). The RRA ensured that the inverse kinematics generated joint angles from the musculoskeletal model closely matched the experimental motion capture data. Muscle forces were estimated with static optimization, and the moment arms were calculated with a muscle analysis tool.

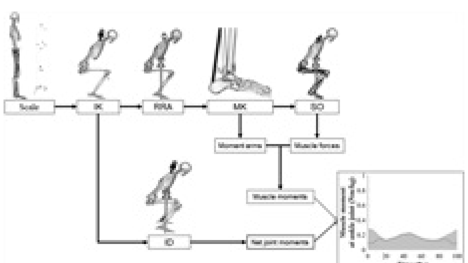


Figure 2.: Workflow of the individual steps during data processing. IK = inverse kinematics; ID = inverse dynamics; RRA = residual reduction algorithm; MK = muscle kinematics; SO = static optimization.

The moment that a muscle created at a joint was calculated by multiplying its estimated muscle force and its instantaneous moment arms of that muscle (Figure 3). Because the musculoskeletal model included multiple muscles that belonged to "functional groups," the moments created by all muscles within that group were summed into a single value. Therefore, the separate portions of the gluteus maximus (GMax—superior, medial, and inferior fibers of the gluteus maximus), hamstrings (HAM—semitendinosus, semimembranosus, and biceps femoris long head), vastii (VAS—vastus lateralis, medialis, and intermedius), and gastrocnemii (GAS—medial and lateral gastrocnemius) were summed into single variables. Other muscles that were included in the current study included the adductor magnus (AddMag), rectus femoris (RF), and soleus (SOL) muscle. Data were analyzed from the beginning to the end of each trial: the beginning and end of each trial were defined as the points where the center of mass of the torso segment fell below and returned to within 0.5% of standing height, respectively. The data were time normalized with 101 data points to range from 0 to 100% of the squat cycle.

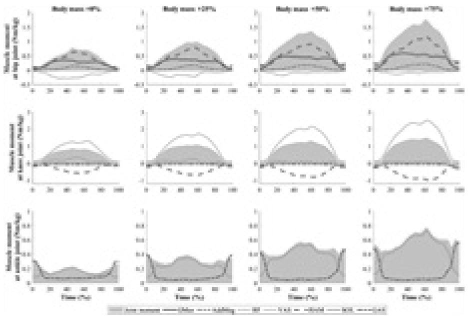


Figure 3.: Muscle contributions to lower extremity net joint moments (N·m·kg^{-1}) in the sagittal plane during squats with 4 different external loads (0, 25, 50, and 75% of body mass). Shaded gray represents the experimental net joint moment determined via inverse dynamics. GMax = gluteus maximus; AddMag = adductor magnus; RF = rectus femoris; HAM = hamstrings; VAS = vastii; SOL = soleus; GAS = gastrocnemii.

Statistical Analyses

Time series data across the different load conditions (0, 25, 50, and 75% of BM) were compared with the SPM analysis of variance (ANOVA) procedure [19–21]. For the SPM procedure, significance thresholds were constructed based on random field theory and used to test time differences in the series data. The SPM procedure used a function similar to a repeated-measures ANOVA to compare time series data from the 4 different load conditions. Significant SPM ANOVA results were followed up with pairwise SPM *t*-tests during post hoc testing. The significance levels for comparing time series data were set to alpha levels of 0.05.

Results

Hip Joint Data

For the hip extension NJM data, the SPM ANOVA procedure indicated a significant main effect of load (Figure 4). Statistical parametric mapping post hoc analysis showed that hip extension NJMs differed among all pairwise load comparisons. Specifically, hip extension NJMs increased with each successive increase in external load. For the muscle-specific contributions to hip extension NJMs, the SPM ANOVA procedure indicated significant main effects of load for the GMax, AddMag, and HAM muscles (Figure 5). Statistical parametric mapping post hoc analysis showed that an increase in load also significantly increased the GMax and HAM moment at the hip.

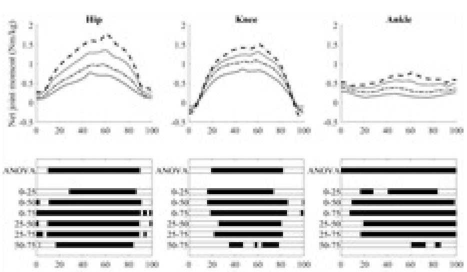


Figure 4.: Top row: hip, knee, and ankle net joint moments (N·m·kg^{-1}) during squats with additional loads of 0% (solid lines), 25% (dash-dot lines), 50% (dotted lines), and 75% (dashed lines) of body mass. Bottom row: results from statistical parametric mapping analysis of variance and post hoc tests. Filled black lines in the bottom row

indicate time points during the squat cycle where the threshold of statistical significance was exceeded during the analysis of variance and pairwise comparisons between the respective loads.

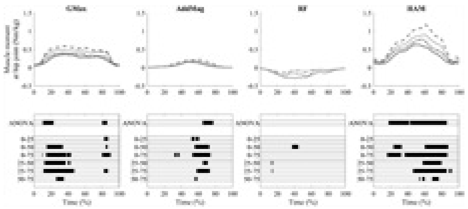


Figure 5.: Top row: sagittal plane joint moments (N·m·kg^{-1}) created by individual hip muscles during squats with additional loads of 0% (solid lines), 25% (dash-dot lines), 50% (dotted lines), and 75% (dashed lines) of body mass. Bottom row: results from statistical parametric mapping analysis of variance and post hoc tests. Filled black lines in the bottom row indicate time points during the squat cycle where the threshold of statistical significance was exceeded during the analysis of variance and pairwise comparisons between the respective loads. GMax = gluteus maximus; AddMag = adductor magnus; RF = rectus femoris; HAM = hamstrings.

Knee Joint Data

For the knee extension NJM data, the SPM ANOVA procedure indicated a significant main effect of load (Figure 4). Statistical parametric mapping post hoc analysis showed that knee extension NJMs differed among all pairwise load comparisons. Specifically, knee extension NJMs increased with each successive increase in external load. For the muscle-specific contributions to hip extension NJMs, the SPM ANOVA procedure indicated significant main effects of load for the RF, VAS, and HAM muscles (Figure 6). Statistical parametric mapping post hoc analysis showed that an increase in load also significantly increased primarily the VAS, and to a smaller extent the HAM, moment at the knee.

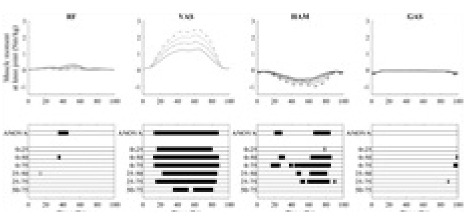
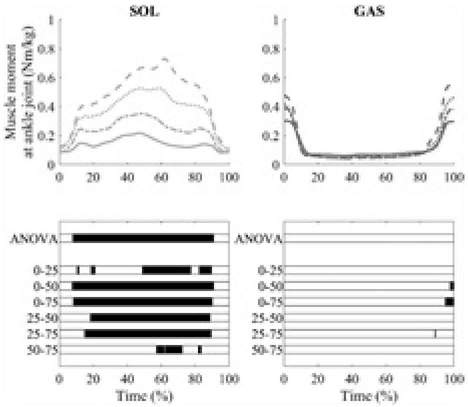


Figure 6.: Top row: sagittal plane joint moments (N·m·kg^{-1}) created by individual knee muscles during squats with additional loads of 0% (solid lines), 25% (dash-dot lines), 50% (dotted lines), and 75% (dashed lines) of body mass. Bottom row: results from statistical parametric mapping analysis of variance and post hoc tests. Filled black lines in the bottom row indicate time points during the squat cycle where the threshold of statistical significance was exceeded during the analysis of variance and pairwise comparisons between the respective loads. RF = rectus femoris; VAS = vastii; HAM = hamstrings; GAS = gastrocnemii.

Ankle Joint Data

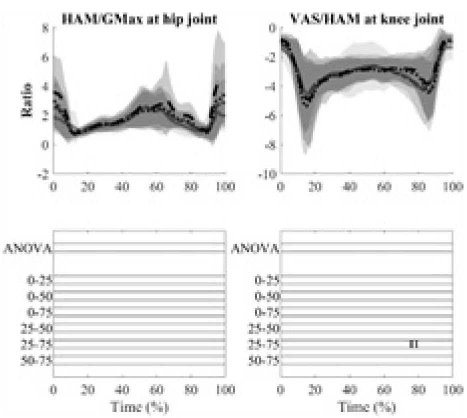
For the ankle plantar flexion NJM data, the SPM ANOVA procedure indicated a significant main effect of load (Figure 4). Statistical parametric mapping post hoc analysis showed that ankle plantar flexion NJMs differed among all pairwise load comparisons. Specifically, ankle plantar flexion NJMs increased with each successive increase in external load. For the muscle-specific contributions to ankle plantar flexion NJMs, the SPM ANOVA procedure indicated significant main effects of load for the SOL muscle (Figure 7). Statistical parametric mapping post hoc analysis showed that an increase in load also significantly increased the SOL moment at the ankle.



[Figure 7.:](#) Top row: sagittal plane joint moments (N·m·kg^{-1}) created by individual ankle muscles during squats with additional loads of 0% (solid lines), 25% (dash-dot lines), 50% (dotted lines), and 75% (dashed lines) of body mass. Bottom row: results from statistical parametric mapping analysis of variance and post hoc tests. Filled black lines in the bottom row indicate time points during the squat cycle where the threshold of statistical significance was exceeded during the analysis of variance and pairwise comparisons between the respective loads. SOL = soleus; GAS = gastrocnemii.

Joint Ratio Data

The ratios of sagittal plane joint moments created by the hamstring and gluteus maximus muscles at the hip joint and by the vastii and hamstring muscles at the knee joint did not differ across any of the external load conditions (Figure 8).



[Figure 8.:](#) Left: ratio between sagittal plane joint moments created at the hip joint by hamstring and gluteus maximus muscles. Right: ratio between sagittal plane joint moments created at the knee joint by vastii and hamstring muscles. Moment data are shown for each external load condition (0% [solid lines], 25% [dash-dot lines], 50% [dotted lines], and 75% [dashed lines] of body mass).

Discussion

The purpose of this study was to determine muscle contributions to lower extremity NJMs in the sagittal plane during squats with different external loads. The results showed that the NJMs at the hip, knee, and ankle increased in tandem with external load. The results further showed that these increases were driven by the gluteus maximus and hamstring muscles at the hip, by the vastii muscles at the knee, and by the soleus at the ankle. Interestingly, the ratio in joint moment contribution from the gluteus maximus and hamstring muscles at the hip did not change across load. Similarly, the ratio between the vastii generated extension moment and hamstring generated flexion moment at the knee did not change across load. Collectively, the results showed how the extension and flexion moments that are generated by individual muscles contribute to the overall NJMs at the joints of the lower extremity during the back squat exercise. In addition, the results identified muscles that most contribute to the observed load-dependent increases of the lower extremity NJMs. Last, the results showed that joint moment generation among synergistic and antagonistic muscles remains constant as external load increases.

The results showed that the hip extension NJMs increased in response to an increase in the external load. In addition, the results also showed that extension moments generated by the gluteus maximus and hamstring muscles at the hip joint increased concomitantly as load increased. Although the hip extension moment generated by the adductor magnus also increased with external load, the magnitude of this moment was smaller than the other hip extensor muscles. As expected, the RF muscle created a flexion moment at the hip joint but was small in magnitude and did not differ across loads. Two findings warrant specific mention; first, the hamstring muscles produced a greater hip extension moment than the gluteus maximus, and second, the ratio between these 2 synergistic muscle groups did not change as load increased. Although it may be a surprise that the hip extension moments generated by the hamstring muscles were almost twice that of the gluteus maximus, Schellenberg et al. [24] previously reported that hamstring muscle forces are greater than gluteus maximus muscle forces during various lower extremity exercises. Another factor to consider in how the force produced by each muscle generates an NJM is the muscle's internal moment arm. For example, the moment arm of the gluteus maximus decreases monotonically with knee flexion angle, which would decrease the muscles' ability to generate an extension moment at the hip [17,18]. In addition, the moment arm of the gluteus maximus is also smaller than the moment arm of the hamstrings throughout most of the hip flexion range of motion, especially at large hip flexion angles [17,18]. As for the ratio in hip extension moments generated by the hamstring and gluteus maximus muscles, not much research has investigated load sharing between hip extensor muscles or used musculoskeletal modeling to determine the contributions from each muscle to hip extension NJMs. Previous models of load sharing have assumed that the hamstring muscles contribute approximately 50% toward the total hip extension NJMs and that this percentage does not change across different external loads [2]. Although the results of the current study question the assumption of equal contribution between muscles, they do support that the ratio does not change as heavier weights are lifted during the back squat. Collectively, these results have several practical implications. First, the results about individual muscle contributions to the overall NJMs suggest that with respect to hip joint mechanics, subjects execute the back squat with large muscle moment contributions from the hamstring and gluteus maximus muscles but not the adductor magnus, which has important implications for the program design process where exercises are selected based on the mechanical demands that they impose on the neuromusculoskeletal system. Second, although the hamstrings were bigger absolute contributors to the hip extension NJMs than the gluteus maximus, increasing the external load did not change their relative contributions and would indicate that the mechanical demands imposed on these muscles remain constant.

The NJMs produced at the knee increased in response to an increase in external load during the back squat. Although the load-dependent increase in knee extension NJMs is well documented for the back squat exercise [5,7,15], no previous studies examined the individual joint moment contributions from the respective extensor and flexor muscles. The results from the current study showed that the load-dependent increases in knee extension NJMs during the squat were accompanied by increases in the joint moments created by the uniarticular knee extensor (i.e., vastii) muscles. Although the RF also created extension moments at the knee joint, the magnitude of these moments was small and did not change across loads. In addition, although the gastrocnemii muscles exhibit the potential to generate a flexion moment at the knee, the results of the current study suggest that its practical effects are almost irrelevant. As expected, the hamstring muscles generated knee joint flexion moments that increased in magnitude as the external load increased. The influence of the knee flexion moments was especially noticeable during the second half (i.e., concentric portion) of the back squat and nicely illustrates the balance between knee extensor and flexor muscles in creating the overall NJMs at the knee joint. With respect to the balance between knee extensor and flexor muscles, it is interesting to note that the ratio between the vastii generated extension moment and hamstring generated flexion moment at the knee did not change across load. So, although solely examining NJMs is often acknowledged as a limitation of studies that investigate biomechanics of resistance training exercises, the constant cocontraction ratio between antagonistic knee joint muscles suggests that NJMs can still provide valuable information about the biomechanical demands imposed on the knee musculature during the back squat exercise. Taken together, these results have several practical implications. First, based on the results of the muscle moments and their contributions to the overall knee extensor NJMs, it appears as though subjects execute the back squat with large contributions from the vastii muscles but small contributions from the RF muscle. This finding would suggest that with respect to exercise selection and training, the back squat would only impose and elicit sufficient mechanical demands and neuromuscular adaptations on the vastii and not on the RF muscle. Second, a constant ratio between vastii and hamstring muscle moments suggests that regardless of load, the mechanical demands imposed on these muscles remain similar and that an increase in load would not be associated with a shift toward a more “quadriceps”-dominant strategy.

Like the hip and knee joint findings, the NJMs produced at the ankle exhibited a load-dependent increase. Although the soleus and gastrocnemii both exhibit the potential to generate plantar flexion moments at the ankle joint, the results of the current study showed that the load-dependent increase in ankle plantar flexion NJMs resulted primarily from greater joint moment generation by the soleus muscle. The relatively smaller contribution by the gastrocnemii muscles toward the generation of ankle plantar flexion moments is likely the result of unfavorable changes in their force-length potential in positions of deep knee flexion [1]. That said, although the ankle NJMs exhibited load-dependent increases, the overall magnitudes of the NJMs were small compared with the other joints Therefore, although the back squat certainly imposes a biomechanical demand on the soleus muscle, this demand is likely too small to lead to any significant functional adaptations and thus does not warrant choosing this exercise to target the soleus.

The results and inferences presented in the current study are subject to several limitations. First, the estimated muscle forces were calculated with a musculoskeletal model and an optimization algorithm. Although the musculoskeletal model has been validated for motions with large hip and knee flexion ranges [3] and was scaled to each subject separately, it is still possible that the model does not completely reflect each subject's musculoskeletal geometry adequately. In addition, muscle forces were calculated with an algorithm that uses static optimization, which solves the problem of muscle redundancy by minimizing the squared sum of activations of all respective muscles within the model. It is possible that using a different optimization criteria or algorithm would alter the results. In addition, the muscle forces that were calculated with the musculoskeletal model were not validated against experimental EMG data, and the use of EMG-informed modeling techniques may improve the accuracy of muscle force calculations. However, this limitation may not adversely affect the results of the statistical analysis because computational errors would be consistent across experimental condition (i.e., load). Another limitation is that the load was chosen based on a percentage of each subject's BM, which may imply that each subject was working at slightly different effort level with respect to their 1 repetition maximum. Last, the loads only ranged from 0 to 75% of subject's BM, which may be considered low for an exercise like the back squat. The results of the current study may therefore be more relevant for situations where loads in these ranges are prescribed, e.g., in the rehabilitation setting where loads are often prescribed based on % of BM because either 1 repetition maximums are not known or unavailable due to injury, etc.

Practical Applications

The practical applications of these findings for strength and conditioning professionals are threefold. First, the results of the current study illustrate how joint moments generated by individual muscles contribute to the overall NJMs at the respective lower extremity joints during the back squat exercise. Second, the results identified which muscles most contribute to the observed load-dependent increases of the lower extremity NJMs as subjects performed the back squat with successively greater loads. Third, the results show that the relative contributions of synergistic and antagonistic muscles to the NJMs during the back squat remain relatively constant as external load increases. Collectively, these practical applications help inform the program design process (e.g., exercise selection) in that they provide specific evidence about the contributions of individual muscle groups during the back squat.

References

1. Arampatzis A, Karamanidis K, Stafilidis S, et al. Effect of different ankle- and knee-joint positions on gastrocnemius medialis fascicle length and EMG activity during isometric plantar flexion. J Biomech 39: 1891–1902, 2006.
2. Bryanton MA, Carey JP, Kennedy MD, et al. Quadriceps effort during squat exercise depends on hip extensor muscle strategy. Sports Biomech 14: 122–138, 2015.
3. Catelli DS, Wesseling M, Jonkers I, et al. A musculoskeletal model customized for squatting task. Comput Methods Biomech Biomed Engin 22: 21–24, 2019.
4. Chiu LZF. Biomechanical methods to quantify muscle effort during resistance exercise. J Strength Cond Res 32: 502–513, 2018.
5. Choe KH, Coburn JW, Costa PB, et al. Hip and knee kinetics during a back squat and deadlift. J Strength Cond Res 2018. doi: 10.1519/JSC.0000000000002908.
6. Delp SL, Anderson FC, Arnold AS, et al. OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Trans Biomed Eng 54: 1940–1950, 2007.
7. Flanagan SP, Salem GJ. Lower extremity joint kinetic responses to external resistance variations. J Appl Biomech 24: 58–68, 2008.
8. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. Sports Med 34: 663–679, 2004.
9. Hug F, Hodges PW, Tucker K. Muscle force cannot be directly inferred from muscle activation: Illustrated by the proposed imbalance of force between the vastus medialis and vastus lateralis in people with patellofemoral pain. J Orthop Sports Phys Ther 45: 360–365, 2015.
10. Izquierdo M, Häkkinen K, Gonzalez-Badillo JJ, et al. Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. Eur J Appl Physiol 87: 264–271, 2002.
11. Kainz H, Modenese L, Lloyd DG, et al. Joint kinematic calculation based on clinical direct kinematic versus inverse kinematic gait models. J Biomech 49: 1658–1669, 2016.
12. Kipp K, Harris C, Sabick MB. Lower extremity biomechanics during weightlifting exercise vary across joint and load. J Strength Cond Res 25: 1229–1234, 2011.
13. Kipp K, Kim H, Wolf WI. Muscle forces during the squat, split squat, and step-up across a range of external loads in college-aged men. J Strength Cond Res 2020. doi: 10.1519/JSC.0000000000003688.
14. Kraemer WJ, Deschenes MR, Fleck SJ. Physiological adaptations to resistance exercise. Implications for athletic conditioning. Sports Med 6: 246–256, 1988.
15. Krzyszkowski J, Kipp K. Load-dependent mechanical demands of the lower extremity during the back and front squat. J Sports Sci 38: 2005–2012, 2020.
16. Maniar N, Schache AG, Cole MH, et al. Lower-limb muscle function during sidestep cutting. J Biomech 82: 186–192, 2019.

17. Nemeth G, Ohlsen H. In vivo moment arm lengths for hip extensor muscles at different angles of hip flexion. J Biomech 18: 129–140, 1985.
18. Neumann DA. Kinesiology of the hip: A focus on muscular actions. J Orthop Sports Phys Ther 40: 82–94, 2010.
19. Pataky TC. Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. J Biomech 43: 1976–1982, 2010.
20. Pataky TC, Vanrenterghem J, Robinson MA. Zero- vs. one-dimensional, parametric vs. non-parametric, and confidence interval vs. hypothesis testing procedures in one-dimensional biomechanical trajectory analysis. J Biomech 48: 1277–1285, 2015.
21. Pataky TC, Vanrenterghem J, Robinson MA. The probability of false positives in zero-dimensional analyses of one-dimensional kinematic, force and EMG trajectories. J Biomech 49: 1468–1476, 2016.
22. Pollock ML, Gaesser G, Butcher JD, et al. The recommended quantity and quality of exercise for developing and maintaining cardiorespiratory and muscular fitness, and flexibility in healthy adults. Med Sci Sports Exerc 30: 975–991, 1998.
23. Riemann BL, Lapinski S, Smith L, et al. Biomechanical analysis of the anterior lunge during 4 external-load conditions. J Athl Train 47: 372–378, 2012.
24. Schellenberg F, Taylor WR, Lorenzetti S. Towards evidence based strength training: A comparison of muscle forces during deadlifts, goodmornings and split squats. BMC Sports Sci Med Rehabil 9: 13, 2017.
25. Winter DA. Kinetics: forces and moments of force. In Biomechanics and Motor Control of Human Movement. John Hoboken, NJ: Wiley & Sons, 2009. pp. 107–138.

Keywords:

Biomechanics, resistance training, exercise, musculoskeletal modeling