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Kinetics, kinematics, and muscle activity patterns during the back squat with different contributions of elastic resistance

Original investigation

Running head: Back squat with different elastic resistance

Authors: Lin Shi[1,2,3], Mark Lyons[4], Michael Duncan[5], Sitong Chen[6], Dong Han[3], Chengbo Yang[7*]

Author affiliations
[1] Center for Strength and Conditioning Training, Chengdu Sport University, Chengdu, China
[2] Center for Post-doctoral Studies of Sport Science, Chengdu Sport University, Chengdu, China
[3] School of Athletic Performance, Shanghai University of Sport, Shanghai, China
[4] Sport and Human Performance Research Centre, University of Limerick, Ireland
[5] Centre for Sport, Exercise and Life Sciences, Coventry University, Coventry UK
[6] Institute for Health and Sport, Victoria University, Melbourne, Australia
[7] School of Sport Training, Chengdu Sport University, Chengdu, China

*Corresponding author
Chengbo Yang
Address: Tiyuan Road No.2, Wuhou district, Chengdu, China
Email: 329628865@qq.com
Phone number: +(86)-13881765366

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Abstract

Purpose: Performing back squat with elastic bands has been widely used in resistance training. Although research demonstrated greater training effects obtained from adding elastic bands to the back squat, little is known regarding the optimal elastic resistance and how it affects neuromuscular performance. This study was to compare the force, velocity, power and muscle activity during the back squat with different contributions of elastic resistance. ***Methods:*** Thirteen basketball players performed three repetitions of the back squat at 85% of 1 repetition maximum across four conditions: 1) total load from free weight; 2) 20%, 3) 30%, and 4) 40% of the total load from elastic band and the remaining load from free weight. The eccentric and concentric phases of the back squat were divided into upper, middle, and bottom phases. ***Results:*** In the eccentric phase, mean velocity progressively increased with increasing elastic resistance, muscle activity of the vastus medialis and rectus femoris significantly increased with the largest elastic resistance in the upper phase ($P \leq 0.036$). In the concentric phase, mean power ($P \leq 0.021$) and rate of force development ($P \leq 0.002$) significantly increased with increasing elastic resistance. Furthermore, muscle activity of the vastus lateralis and vastus medialis significantly improved with the largest elastic resistance in the upper phases ($P \leq 0.021$). ***Conclusion:*** Velocity, power, rate of force development, and selective muscle activity increased as the elastic resistance increased in different phases during the back squat exercise.

Keywords: variable resistance training, elastic band, power, rate of force development, electromyography

Introduction

Back squat is one of the most widely prescribed exercises in resistance training and is traditionally performed with a constant external load. Owing to joint angle influences, the maximal load that can be lifted is dependent on the initial concentric phase and more specifically, the sticking region (i.e., the range of motion where a large increase in the difficulty to continue the lift is experienced).[1] This can have two consequences: 1) high load can cause the velocity to decrease in the initial concentric phase,[2,3] thus potentially limiting the power output; 2) as the joints extend, the muscle force potential gradually exceeds the load provided in the remaining phase. Therefore, a constant external load may not optimize neuromuscular performance during the back squat. The addition of elastic bands to the back squat (termed variable resistance training (VRT)), has been proposed as an alternative to optimize neuromuscular performance throughout the range of motion.[4,5] More specifically, by reducing the free weight load, there is potential to alleviate the negative effects (e.g., decreased velocity[2]) of the sticking region caused; as the joints extend to the range of motion where the muscles can produce more force, the external load is accordingly increased to a greater extent. Empirical evidence supports that a larger contribution of the elastic resistance results in greater velocity,[6,7] force,[6,8] power output,[6,9] and muscle activation[10] compared to when a lower contribution of the elastic resistance is used. However, Heelas et al.[7] compared the effect of 20 kg, 25 kg, and 30 kg elastic resistance on muscle activity during the deadlift. A significant decrease in electromyography (EMG) was observed in the medial gastrocnemius (MG) and semitendinosus as the elastic resistance increased. This is likely attributed to their VRT design strategy used, the load was equal between VRT and constant resistance training (CRT) at the upper position. Similarly, Nijem et al.[11] utilized the aforementioned VRT design and observed significantly decreased peak force and gluteus maximus EMG in the VRT condition (20% of the total load from elastic resistance) compared with the CRT condition. Therefore, using a large contribution of the variable resistance to optimize neuromuscular performance is attractive as the effects are clearly influenced by the VRT design strategy.

A recent meta-analysis compared the acute effects of different VRT design strategies on force, velocity, and power output.[5] In comparison with the strategies using an equalized load at the bottom/top position, the results showed that VRT using an equated loading scheme (i.e., lower load at the bottom and higher load at the top in the VRT compared to the CRT) was more likely to increase mean power output.[5] However, Wallace et al.[8] examined the effect of kinetics during the back squat with different contributions of elastic resistance in 60% and 85% of one repetition maximum (1RM) conditions, respectively. A decrease in power output was noted when using 35% of the total load from elastic resistance compared to a total load of 20% in the 85% 1RM condition. It is noteworthy that there were slight improvements in force and rate of force development (RFD) with the larger elastic resistance compared to the lower one[8]. Their findings indicate that a larger elastic resistance leads to a more pronounced reduction in velocity, resulting in decreased power output. Similarly, Heelas et al.[7] reported that velocity and power began to plateau during the deadlift as the elastic resistance increased to 30% of total load in the 54% 1RM condition. From the above, there appears to be a threshold for elastic resistance that limits power output. Although some studies have investigated the acute effects of different contributions of elastic resistance, such as Swinton et al.[12] who compared the effects of 20% 1RM and 40% 1RM from elastic resistance in 30% 1RM, 50% 1RM, and 70% 1RM conditions, respectively, and Kubo et al.[6] who compared the effects of 20%, 40%, and 80% of the total load from elastic resistance in the 56% 1RM condition, a low free weight load used in these studies limits the applicability to practice. In addition, anecdotal information indicates that the elastic resistance at the top position may increase the eccentric velocity, which enhances the efficacy of the stretch-shortening cycle (SSC)[13]. Although some studies demonstrated an increased peak eccentric velocity in the VRT compared to the CRT,[14,15] no significant difference in mean eccentric velocity was found,[15] likely caused by the VRT design strategy used.[5]

Based on the variable results, it is necessary to further elucidate the acute effects of different contributions of elastic resistance using an equated loading scheme. This could provide comprehensive information that will inform future prescription of VRT strategies. The purpose of the study therefore was to compare force, velocity, power, RFD, and EMG during the back squat with 20% (20%VRT), 30% (30%VRT), and 40% (40%VRT) of the total load from elastic resistance in a cohort of male basketball players. It is hypothesized that as the elastic resistance increases, 1) velocity will increase in the eccentric phase; 2) the power output and RFD will increase in the concentric phase; 3) 40%VRT will limit power output compared to the other conditions and 4) muscle activation will increase in the upper phase of the back squat.

Methods

Study design

The study used a randomized, counter-balanced, cross-over design to compare the force, velocity, power, RFD, and EMG of the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF), biceps femoris (BF) and MG during the back squat in CRT and VRT conditions. The back squat in the CRT condition was performed at 85% of 1RM whereby the total load came from free weight. In VRT conditions, the elastic resistance produced approximately 17%, 25%, and 34% 1RM at the top position of the back squat in 20%VRT, 30%VRT, and 40%VRT conditions, respectively. The free weight was removed by half of the elastic resistance (e.g., 17% 1RM was removed from the free weight in 40%VRT condition) to make a lower load at the bottom and a larger load at the top position, as previously described.[8] Therefore, the average load was equal across the range of motion in all VRT conditions in comparison with the CRT condition. The dependent variables were analyzed in different phases and the whole in the eccentric and concentric phases.

Participants

Fourteen well-trained male collegiate basketball players, certified at least national II level of basketball performance, volunteered for this study. Thirteen participants (age: 20.5 ± 0.9 years; height: 188.5 ± 8.5 cm; body mass: 82.8 ± 12.9 kg) completed the study, with one participant withdrawing for personal reasons. Most of them performed recreational resistance training for 6 months prior to the study (back squat 1RM relative to body mass: 1.4 ± 0.3). A *priori* power analysis with effect size of 0.4, power of 90%, an α error of 0.05 was conducted, the estimated sample size was 12 participants. All participants had no current musculoskeletal injury that could affect them performing a back squat exercise and were required to refrain from high intensity exercises 24 hours before testing. Written informed consent was obtained from participants before the beginning of the study. Ethical approval was granted by the Shanghai University of Sport Science Research Ethics Committee in accordance with the Helsinki Declaration.

Procedures

Prior to the experiment, three sessions were conducted to familiarize participants with the VRT in two weeks. In the fourth familiarization session, participants completed back squat 3RM testing, then the 1RM was estimated based on the formula by the National Strength and Conditioning Association.[16] First, participants performed a general warm-up including 5 minutes of low-intensity running followed by 10 minutes of dynamic stretching exercises, which was identical in all sessions. Then, participants were instructed to perform 7−10, 5−7, and 3−5 repetitions at 50%, 70%, and 80% of the estimated 1RM, respectively. 2 minutes recovery was provided. Further, participants completed 3 to 4 trials at their estimated 3RM with correct back squat technique. 4 minutes recovery followed. Participants were required to squat to a 90° knee angle. The last familiarization session was used to measure the elastic band (Rising, Nantong, China) resistance following the previous protocol.[15] Shortly, participants stood on a force plate (Kistler, model 9290AA, Winterthur, Switzerland) with an unloaded barbell to measure the target elastic resistance using a trial-and-error method.[15] The actual elastic resistance for 20%VRT, 30%VRT, and 40%VRT were 1.42 (± 1.44) to 17.36 (± 2.53), 2.66 (± 2.18) to 24.8 (± 2.4), and 2.76 (± 2.53) to 33.84 (± 2.7) % 1RM at the bottom and top position of the back squat, respectively.

In the experimental session, following the general warm-up, the participant's skin was shaved and washed with alcohol. The electrodes were placed over the VL, VM, RF, BF, and MG in the direction of the underlying muscle fibers on the dominant leg (referred to the leg kicking the ball) (Figure 1) according to the recommendations by SENIAM (www.seniam.org). A reflective marker was placed on the center of the barbell to track the trajectory of the barbell; the other reflective markers were placed on the pelvis and greater trochanter, medial and lateral malleoli, first and fifth metatarsal heads, toe, and heel (Figure 1). The electrodes and markers were placed by the same researchers for consistency.

FIGURE 1 HERE

Prior to the testing, two submaximal and three maximal vertical jumps were conducted. Two minutes later, participants stood on the force plate to perform one set of three repetitions of the back squat in the CRT, 20%VRT, 30%VRT, and 40%VRT in a random order with at least 48 hours between conditions (Figure 2). During the back squat, participants were instructed to bend their knees in a self-paced but controlled manner with the upper leg being parallel to the ground, and then execute the concentric phase as fast and forcefully as possible. Strong verbal encouragement was given to the participants across all conditions.

FIGURE 2 HERE

Data collection and processing

EMG was recorded using a Ultium-EMG sensor system (Noraxon Inc, Scottsdale, AZ, USA) with a sampling rate of 2000 Hz. A force plate with a sampling frequency of 1000 Hz was used to collect the vertical ground reaction force. A three-dimensional motion capture system (Qualisys, Gothenburg, Sweden) with eight cameras sampling at a frequency of 200 Hz was used to track markers. Three systems were synchronized via Qualisys Track Manager software (Qualysis Oqus 400, Gothenburg, Sweden).

Raw kinetic and kinematic data were imported to Visual 3D (C-motion Inc, Germantown, USA) for segment modelling and analyses. Data were smoothed using a Butterworth fourth-order filter with a cutoff frequency of 10 Hz. Velocity was calculated using a first-order derivative of the barbell displacement data. Power was calculated as the product of the synchronized barbell velocity and vertical ground reaction force data. RFD was determined between the first minimum and maximum force during the concentric phase. The concentric and eccentric phases were determined by the barbell velocity.[15,17] Thereafter, the concentric and eccentric phases were equally divided into three phases (upper, middle, and bottom) based on the barbell displacement data.

The raw EMG data was converted to a custom script written in MATLAB software (MATLAB, version R2020b, MathWorks Inc., Natick, USA). The signal was full wave rectified and bandpass (fourth-order Butterworth filter) filtered with a cutoff frequency of 10-400Hz, and then converted to root of mean square (RMS). RMS was normalized with the peak RMS value during the first repetition of the back squat for each participant.[11] For all dependent variables, three repetitions were averaged in different phases and the whole of the concentric and eccentric phases for further analyses.

Statistical analyses

All data were expressed as mean ± SD. The Shapiro-Wilk test was used to assess normality. One-way repeated-measures analysis of variance (ANOVA) was used to compare each dependent variable in different phases and the whole of the concentric and eccentric phases across conditions. If significant differences were found, Bonferroni post hoc comparisons were performed. The effect sizes were evaluated with η^2, whereby 0.01, 0.06, 0.14 were considered small, moderate, and large, respectively.[18] Statistical significance was set at $P \leq 0.05$ (version 25.0. SPSS Inc., Chicago, IL, USA).

Results

Force

The force outcomes between conditions are presented in Figure 3. In the eccentric phase, there were highly significant differences in peak and mean force in the upper and bottom phases ($F = 8.6 - 21.3$, $P < 0.001$, $\eta^2 \geq 0.419$). Post hoc comparisons revealed that peak and mean force significantly increased in all VRT conditions compared with the CRT condition in the upper phase (+1.02 – +1.56 N/kg, $P \leq 0.02$); in contrast, peak and mean force significantly decreased in all VRT conditions compared with the CRT condition in the bottom phase (-0.77 – -1.54 N/kg, $P \leq 0.026$).

In the concentric phase, there was a highly significant difference in peak and mean force ($F = 3.3 - 19.8$, $P < 0.032$, $\eta^2 \geq 0.214$). Post hoc comparisons showed that peak and mean force significantly decreased in all VRT conditions compared with the CRT condition in the bottom phase (-0.65 – -1.25 N/kg, $P \leq 0.036$). Mean force significantly increased in both 30%VRT and 40%VRT conditions compared with the CRT condition in the upper phase (+2.02 – +2.73 N/kg, $P \leq 0.036$).

FIGURE 3 HERE

Velocity

The velocity outcomes between conditions are presented in Figure 4. In the eccentric phase, there was a significant difference in peak and mean velocity in the upper and bottom phases ($F = 3 - 4.72$, $P \leq 0.043$, $\eta^2 \geq 0.2$). There was a significant difference in mean velocity in the whole movement ($F = 4.3$, $P = 0.011$, $\eta^2 = 0.263$). Post hoc comparisons revealed that only mean velocity significantly increased in the 30%VRT compared to the CRT in the bottom phase (+0.052m/s, $P = 0.019$).

In the concentric phase, there were significant differences in peak and mean velocity in the bottom and upper phases ($F = 3.2 - 28.8$, P 0.034, $\eta^2 \geq 0.211$). There was a significant difference in mean velocity in the whole movement ($F = 15.8$, $P < 0.001$, $\eta^2 = 0.568$). Post hoc comparisons showed that mean velocity significantly increased in all VRT conditions compared with the CRT condition in the bottom phase (+0.064 − +0.104m/s, $P \leq 0.003$). For the whole movement, mean velocity significantly increased in both 30%VRT and 40%VRT conditions compared with the CRT condition (+0.076 − +0.101m/s, $P \leq 0.001$).

FIGURE 4 HERE

Power

The power outcomes between conditions are presented in Figure 5. In the concentric phase, there were significant differences in mean power in the bottom and upper phases ($F = 14.9 - 24.1$, $P < 0.001$, $\eta^2 \geq 0.554$). There were significant differences in mean power and RFD in the whole movement ($F = 19.4 – 20.5$, $P < 0.001$, $\eta^2 \geq 0.617$). Post hoc comparisons showed that mean power significantly increased in all VRT conditions compared with the CRT condition in the bottom and upper phases and the whole movement (+1.06 – +3.22w/kg, $P \leq 0.021$). RFD significantly increased in all VRT conditions compared with the CRT condition (+3.12 – +5.56N/s·kg, $P \leq 0.002$).

FIGURE 5 HERE

Electromyography

The normalized RMS outcomes between conditions are presented in Figure 6 and Figure 7. In the eccentric phase, there were significant differences in RF and VM RMS in the upper phase ($F = 6.8 - 8.1$, $P \leq 0.002$, $\eta^2 \geq 0.493$). Post hoc comparisons revealed that the RF and VM RMS significantly increased in the 40%VRT compared to the CRT (+15.2 − +18.4%, $P \leq 0.036$).

In the concentric phase, there were significant differences in VL and VM RMS in the upper phase ($F = 5.3 - 5.4$, $P = 0.005$, $\eta^2 \geq 0.37$) and the VL EMG in the whole ($F = 4.74$, $P = 0.009$, $\eta^2 = 0.345$). Post hoc comparisons showed that the VL and VM RMS significantly increased in the 40%VRT compared to the CRT in the upper phase (+15.5 − +17.9%, $P \leq 0.021$).

FIGURE 6 AND FIGURE 7 HERE

Discussion

This study compared force, velocity, power, RFD, and muscle activity during the back squat with or without different contributions of elastic resistance. Considering the gradually changing load during the VRT and the equalized load (i.e., the load is equal at the middle position) between VRT and CRT used in the present study, the eccentric and concentric phases were therefore divided into 6 phases, which would fully elucidate the advantages or disadvantages of the VRT.

Results of the eccentric phase supported the hypotheses that greater velocity and EMG occurred as the elastic resistance increased. The increased velocity in the upper phase could be explained by the largest elastic resistance that pushes the individual downward.[4] This was also supported by Stevenson et al.[15] who found a greater peak eccentric velocity during the VRT compared to the CRT. However, no significant difference was observed with regards mean eccentric velocity.[15] This may be caused by the equalized load at the bottom between two training modalities. In the present study, the load was lower at the bottom of the back squat in all VRT compared to the CRT; results showed that the eccentric velocity increased in this phase of the lift in the VRT, and the magnitude of the improvement was greatest in the 40%VRT condition. The finding is consistent with previous findings reporting an increased peak eccentric velocity during the VRT where the load was equal at the upper position between the two.[14] The author concluded that eccentric unloading at the bottom position is a better way to optimize the SSC due to the compliant series elastic component.[14] Based on the above, the increased eccentric velocity in the current study could be attributed in the main to the larger elastic resistance and unloading in the upper and bottom phases, respectively.

The results of this study found a greater activation in RF and VM muscles in the eccentric upper phase in the 40%VRT compared to the CRT, which concurs with previous study.[10] Thus, the hypothesis, that the EMG will increase in the upper phase as the elastic resistance increased, can be partially accepted. Simply put, the muscle is capable of generating more forces during eccentric action than concentric contraction.[19] Thus, more loads in the eccentric upper phase in the VRT can accommodate the ability that the muscles produce more forces, which evidenced by the increased EMG. The current study found greater EMG and force in the eccentric bottom phase compared to the eccentric upper phase in all conditions. This suggests that subjects required more forces to decelerate in the eccentric bottom phase, resulting in greater EMG. However, no significant differences in EMG for any muscle were observed between conditions in the eccentric bottom phase, which is surprising considering the external load decreased in this phase in the VRT. One possible explanation is that a greater number of activated α-motoneurons (i.e., increased EMG) in the eccentric upper phase in the VRT compared to the CRT may remain active in the eccentric bottom phase due to a shorter eccentric action period (improved velocity in the VRT), therefore reducing the EMG difference between conditions. This needs to be evaluated in future trials to more fully elucidate.

In the concentric phase, both mean velocity and power improved as the elastic resistance increased in the bottom and upper phases and the whole movement, which is consistent with the second hypothesis. Specifically, in the bottom phase, although the VRT resulted in significantly decreased force compared with the CRT, a greater velocity obtained in the VRT had a more positive influence on power output. The findings are consistent with a previous study[6] where the concentric phase of the back squat was divided into acceleration and deceleration sub-phases, and a decreased mean force and increased mean velocity and power were observed in the acceleration sub-phase in the VRT.[6] From the above, it seems that despite there was a decrease in force production in the bottom phase of VRT, individuals were able to greatly accelerate the movement, potentially improving their power output.

For the middle phase of the concentric phase, only mean force significantly decreased in the 40%VRT compared with the CRT while other outcomes were not significantly different. This can be explained by the fact that the load was theoretically equal in the middle phase between conditions. Specifically, the differences in both force and velocity reduced between conditions from the bottom to the middle phase, related to increased elastic resistance. As a consequence, the results of the power output and muscle activation did not show any statistically differences between conditions.

When the movement extends to the upper phase, the mean power significantly improved in the VRT, which mainly resulted from the increased mean force. Interestingly, a slight improvement in velocity was found in the VRT, which contrasts other reports of a decreased velocity in the VRT when load is higher.[15,20] In the current study, a higher load was just provided in the biomechanically advantageous position (i.e., the upper phase) during the VRT, resulted in improved force production and EMG. Thus, it could be speculated that the small upper phase velocity improvements may result from optimized force production. In addition, the third hypothesis, that the 40%VRT would limit the power output, can only be partially accepted as the peak power began to plateau in comparison with the 30%VRT. Further research that using larger elastic resistance (e.g., 50% of the total load) to investigate this aspect is needed.

For the whole concentric phase, no significant differences in force and muscle activation were noted between conditions, attributed to the fact that the outcomes in the bottom and upper phases counteracted each other. Similarly, the improved mean velocity and power in the VRT conditions can also be explained by the greater velocity and power obtained in the bottom and upper phases, thus accepting the second hypothesis. In addition, RFD improved significantly as the elastic resistance increased, which is consistent with Galpin et al.[9] who demonstrated a significantly improved RFD in the 35%VRT compared with the 15%VRT and CRT in the 85% 1RM condition. In the current study, the time interval of the RFD was found in the bottom and upper phases in all conditions. In this case, it is understandable that the 40%VRT condition could achieve the peak force in a shorter time due to the improved velocity in the initial concentric phase, thus improving the RFD.

Some limitations need to be acknowledged. Due to the participants had no experiences with VRT prior to the study, the findings may limit the applicability to more experienced athletes that have used VRT. Further research is required to explore whether training experience in VRT affects the biomechanical patterns of the back squat. Additionally, only males were recruited to the study, it is unclear whether the findings are generalized to females. Another limitation is that the load was not enough to induce a clear sticking region in most participants. Only three participants showed decreased concentric velocity in all four conditions. Statistical analyses were not conducted for the kinematics and EMG changes in the sticking region.

Conclusions

During the eccentric phase of the back squat, velocity increased with larger elastic resistance. The RF and VM muscles showed higher activation in the upper phase with the largest elastic resistance. In the concentric phase, larger elastic resistance led to a significant increase in mean power, especially in the bottom and upper phases, as well as in RFD.

The VL and VM muscles showed higher activation in the upper phases with the largest elastic resistance. Of note, peak velocity and peak power slightly decreased in the late concentric phase in the 40%VRT condition. These findings are important for athletes seeking to improve power and RFD as part of their resistance training program and point to the potential of using elastic resistance to achieve these aims.

Acknowledgments

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FIGURES

Figure 1. EMG and reflective markers setup

Figure 2. Elastic bands setup of the back squat

Figure 3. Force outcomes in the concentric and eccentric phases. *Statistically significant difference to CRT; #Statistically significant difference to 20%VRT. Triangle denote results for the whole phase.

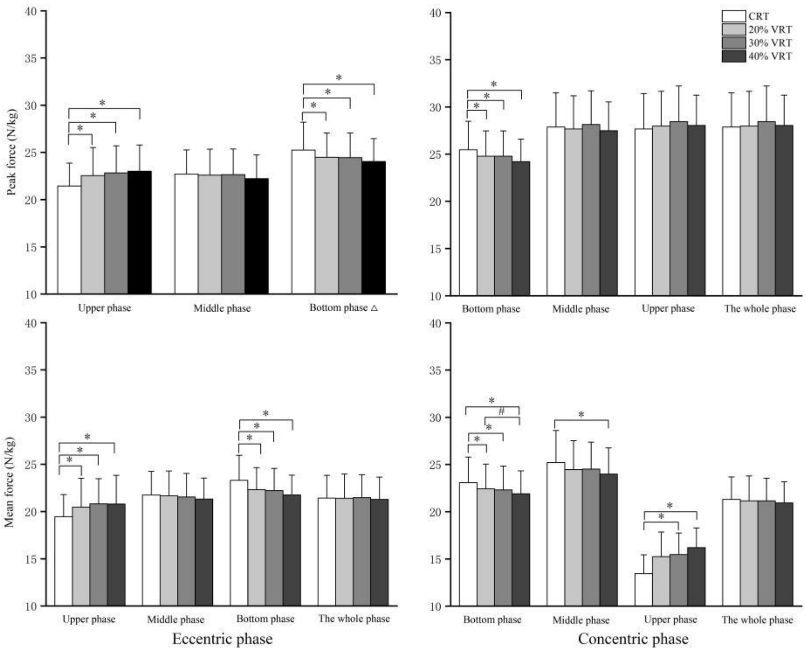


Figure 4. Velocity outcomes in the concentric and eccentric phases. *Statistically significant difference to CRT; #Statistically significant difference to 20%VRT. Triangle denote results for the whole phase.

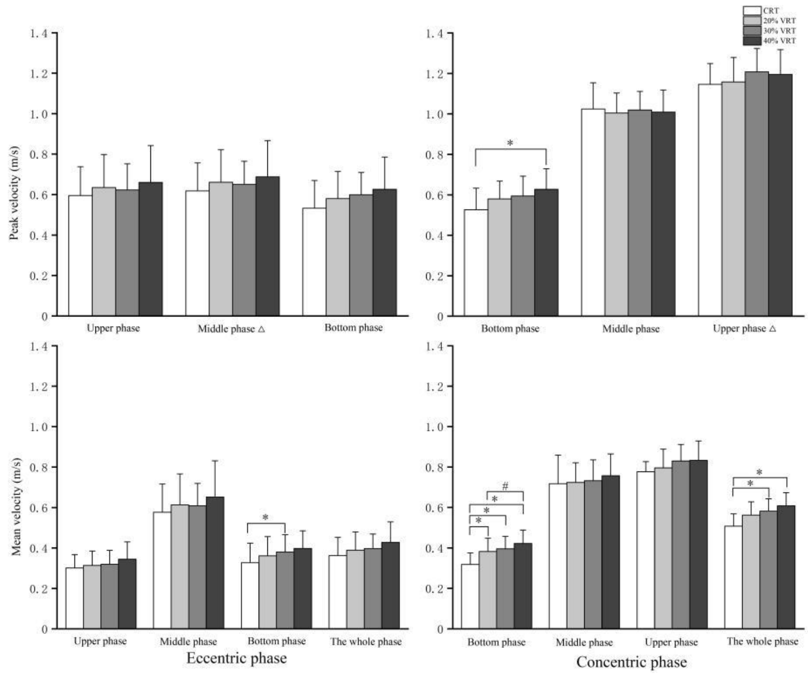


Figure 5. Power outcomes in the concentric phase. *Statistically significant difference to CRT; #Statistically significant difference to 20%VRT. Triangle denote results for

the whole phase.

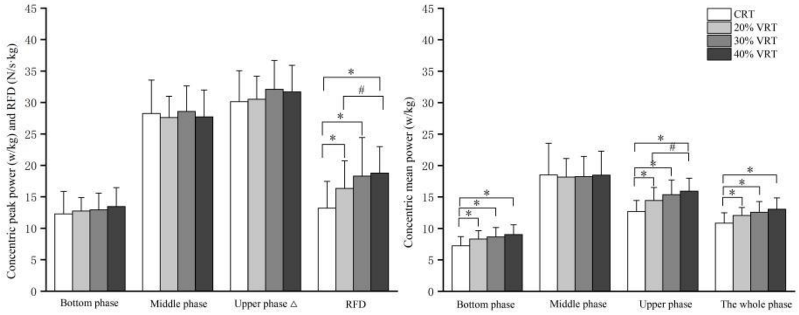


Figure 6. Normalized RMS outcomes of rectus femoris, vastus lateralis, and vastus medialis muscles in the concentric and eccentric phases. *Statistically significant difference to CRT; #Statistically significant difference to 20%VRT.

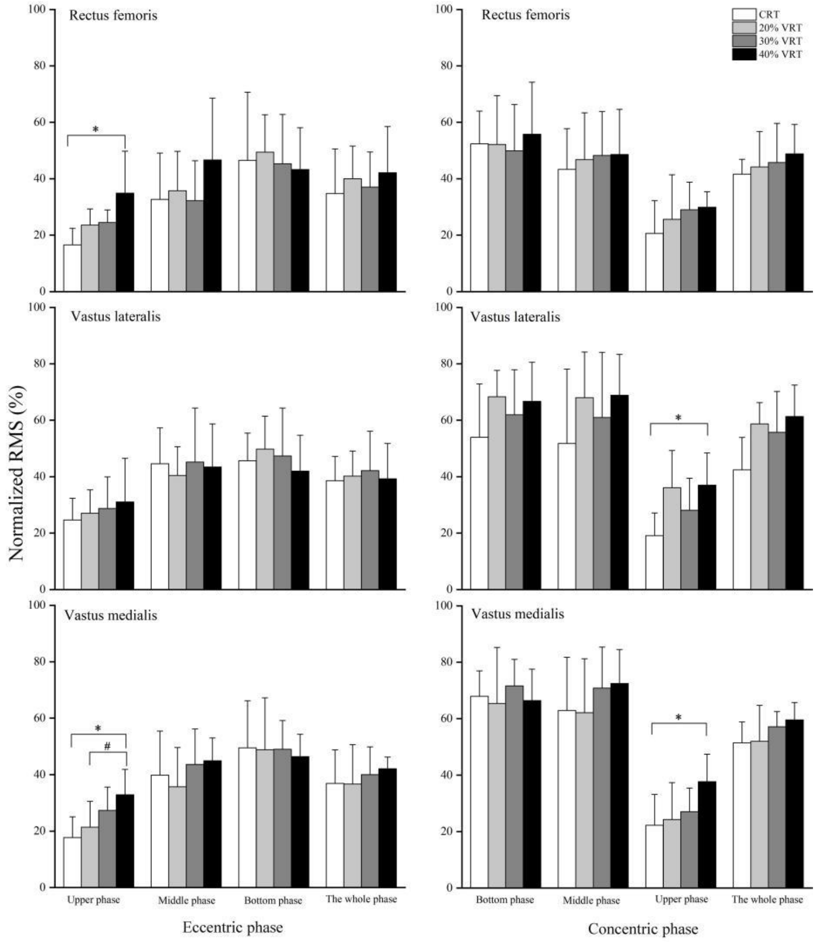
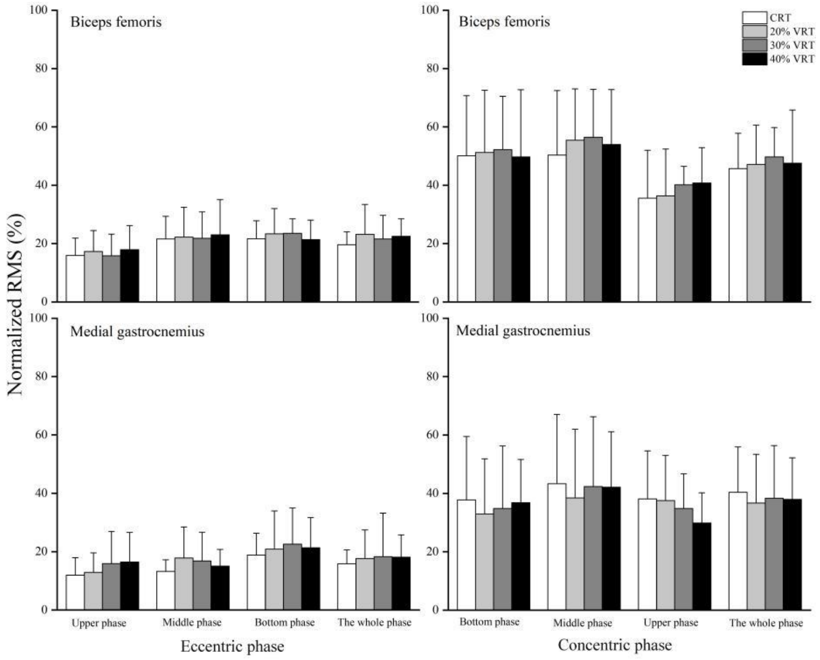


Figure 7. Normalized RMS outcomes of biceps femoris and medial gastrocnemius muscles in the concentric and eccentric phases.



Biceps femoris
Biceps femoris
CRT
20% VRT
30% VRT
40% VRT
Medial gastrocnemius
Medial gastrocnemius
Normalized RMS (%)
100
80
60
40
20
0
Upper phase
Middle phase
Bottom phase
The whole phase
Bottom phase
Middle phase
Upper phase
The whole phase
Eccentric phase
Concentric phase

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