INFLUENCE OF EXTERNAL LOAD AND ECCENTRIC PHASE DURATION ON FORCE PRODUCTION IN THE REAR FOOT-ELEVATED SPLIT SQUAT

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The purpose of this case study was to investigate the effects of external load and eccentric phase duration on peak vertical ground reaction force (vGRF) during the rear foot-elevated split squat (RFESS). One resistance-trained male performed RFESS using 40%, 55%, 70% and 85% of 1-repetition maximum loads under two conditions: self-paced versus 2-s eccentric duration. Preliminary results showed that increasing the load from 40% to 85% 1-RM led to a mean increase in peak vGRF of 247 ± 76 N. Interestingly, the peak vGRF was always higher in the self-paced condition compared with the 2-s eccentric condition (mean difference = 151 ± 46 N across 4 loads). This case study shows that moderate external loads may achieve similar peak vGRF compared to heavy external loads, and that a fast eccentric phase could be beneficial for increasing peak vGRF in the RFESS.

KEYWORDS: resistance training, Bulgarian split squat, ground reaction force.

INTRODUCTION: The rear foot-elevated split squat (RFESS)[Figure 1] is a commonly used unilateral lower-body resistance training (RT) exercise. It has been previously shown to reduce inter-limb asymmetries and improve single-leg power (Gonzalo-Skok et al., 2017). The RFESS is also sometimes implemented in favour of the back squat, as it is thought to have a lower mechanical load on the spine due to lower external load and less trunk flexion. However, despite its popularity as a training modality, research into the biomechanics of the RFESS is scarce. Whilst the application of the RFESS in practice is mostly as an RT tool, insights into its biomechanical underpinnings are important to both scientists and coaches alike. This is because one of the primary ways to achieve the desired adaptations from RT is to manipulate the task constraints to elicit specific force-time profiles from the musculoskeletal system. Apart from choosing the RT exercise, the primary way of changing the task constraints is via external load and coaching instructions. Both options can greatly affect the resultant force and its derivatives.

Figure 1: The rear foot-elevated split squat using a specialised barbell from the sagittal view.

Previously, Helme et al. (2019; 2022) investigated the RFESS across different external loads using two force platforms - one for the lead, and one for the rear legs. They reported the mean vertical ground reaction force (vGRF) over the entire RFESS duration including the eccentric and concentric phases. However, since mean vGRF in a non-ballistic movement is always equal to the system weight, mean vGRF is invariant to movement strategy and may not be suitable to guide RT prescription. Quantifying the peak vGRF, a variable that is commonly utilised to assess the intensity of an RT exercise, may be a viable alternative to better understand how external load affects force production during the RFESS. Additionally, it is of interest to explore how the coaching instructions regarding the duration of the eccentric phase affect peak force. Specifically, whether a self-paced strategy results in different peak force relative to a slower, time-controlled eccentric phase. This is of relevance as strength and conditioning professionals typically prescribe performing RT exercises as fast as possible, whereas sports science research may sometimes control the eccentric phase duration for consistency or safety reasons. Understanding how eccentric phase instructions affect peak force production is important for both study design and cross-study comparison, especially if there is an interaction with external load. Furthermore, practitioners may benefit from information on whether peak forces can be modulated by coaching instructions. Thus, the purpose of this case study was to investigate how external load and eccentric phase duration influence peak force in the RFESS.

METHODS: This study was approved by the Nanyang Technological University Institutional Review Board (IRB-2023-1017). One healthy male (age = 25.4 years, height = 1.79 m, mass = 77.4 kg) with more than 5 years of RT experience participated in this case study. Written informed consent was obtained from the participant prior to data collection. At the time of data collection, the participant was free of any musculoskeletal injuries or ailments that could affect the RFESS. Prior to the data collection, the participant performed two familiarisation sessions, that had the identical protocol to the testing session. After two days of rest, the participant underwent 1 repetition maximum (RM) testing following the instructions from the National Strength and Conditioning Association. To test the effect of external load on peak vGRF, the participant performed 4 successful repetitions of RFESS under loads equal to 40%, 55%, 70%, and 85% of his 1 repetition maximum (1-RM). The RFESS was performed with the rear foot elevated on a box equal to the height of the base of the tibial tuberosity from the ground, with a self-selected stance width (medio-lateral distance between the feet) and stance length (length between the lead and rear feet). The dorsum of the rear foot was in contact with the surface of the rear box. From this position, after having picked up the specialised barbell, the participant was instructed to descend to the point where the front thigh was parallel to the floor, thereafter standing up as fast as possible. All of the testing was done only on the dominant leg (self-identified by the participant).

Two days after the 1-RM testing session, the participant performed the RFESS using 40%, 55%, 70%, and 85% 1-RM loads for 4 repetitions under self-paced, and 2-s metronome-controlled eccentric phase conditions. The order of external loads was randomised. The participant was instructed and verbally encouraged to execute the concentric phase as fast as possible in both conditions. The range of loads chosen represents the intensity that is utilised to train power and maximal strength in RT sessions.

To collect the vGRF data, two force platforms were used: Kistler 9287BA under the lead leg, and Kistler 9260AA3 under the rear leg. The data were collected using the BioWare software with sampling at 1000 Hz. For data analysis, the vGRF from the lead and the rear force platforms were combined to calculate the total vGRF. The peak force was identified as the highest vGRF throughout the whole repetition of the RFESS. Instantaneous velocity was calculated as the time integral of acceleration, with the bottom position identified as the time-point where velocity transitions from negative to positive.

RESULTS: During the 1-RM testing, the subject achieved the heaviest external load of 106 kg, displaying a relative strength of 1.37 body mass. The participant achieved a higher peak vGRF during the self-paced conditions compared to the 2-s eccentric trials at all 1-RM intensities [Table 1]. Conversely, the peak concentric velocity was higher in the 2-s eccentric condition for all external loads. Generally, peak vGRF increased with external loads, whereas peak velocity decreased in both conditions. It is worth noting that the peak vGRF in the 85% 2-s eccentric condition remained lower than that of the 70% 1-RM self-paced condition by 58 N.

Table 1. Peak force and peak concentric velocity in the the rear foot-elevated split squat (RFESS) at different external loads and eccentric phase instructions

External Load	Peak vGRF in Self-Paced Condition (N)	Peak vGRF in 2-s Eccentric Condition (N)	Peak Concentric Velocity in Self-Paced Condition (m/s)	Peak Concentric Velocity in 2-s Eccentric Condition (m/s)
40% 1-RM (43.5 kg)	2124 ± 58	1950 ± 49	1.05 ± 0.03	1.11 ± 0.06
55% 1-RM (56 kg)	2137 ± 100	1940 ± 38	0.81 ± 0.03	1.05 ± 0.04
70% 1-RM (76 kg)	2297 ± 58	2154 ± 32	0.68 ± 0.04	0.77 ± 0.07
85% 1-RM (91 kg)	2329 ± 59	2239 ± 33	0.57 ± 0.08	0.64 ± 0.04

RM - repetition maximum; vGRF - vertical ground reaction force.

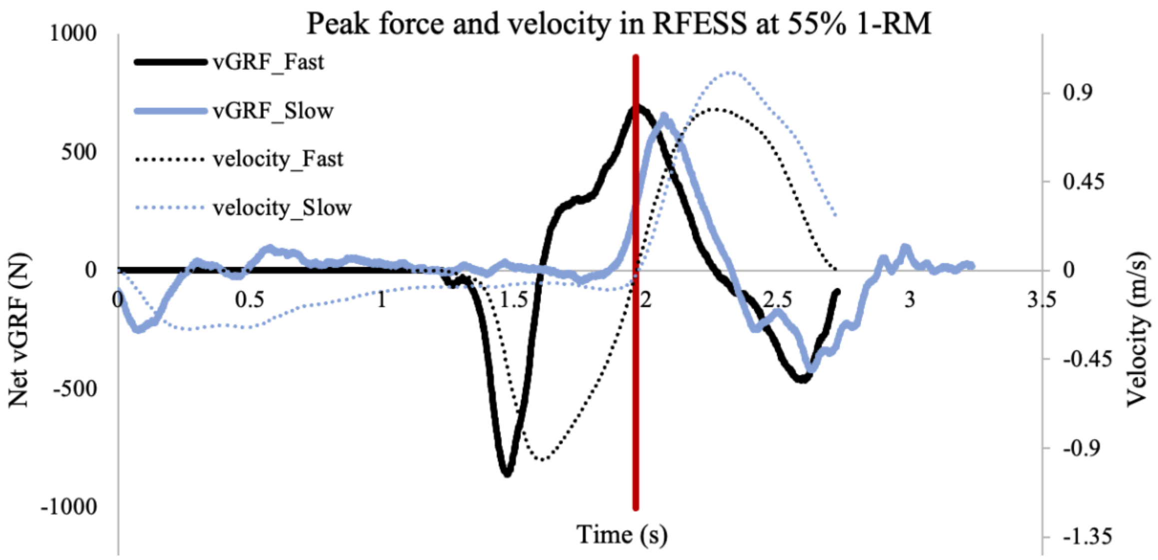

Figure 2: vertical ground reaction force (vGRF) and velocity at 55% 1-repetition maximum (RM) in self-paced (fast) versus 2-second eccentric phase (slow) conditions in the rear foot-elevated split squat (RFESS). The red line demarcates the onset of the concentric phase.

DISCUSSION: The present case study examined the influence of external load and duration of the eccentric phase on peak force and concentric velocity in the RFESS on a trained participant. Similarly to other studies investigating lower-body RT exercises, there was a trend for higher peak vGRF and lower peak concentric velocity with higher 1-RM intensities (Kellis et al., 2005). Whilst peak vGRF was higher in the self-paced condition, the opposite was true for peak concentric velocity.

One reason for observing higher peak vGRF in the self-paced condition compared to the 2-second eccentric condition is likely due to differences in the unloading phase. The much faster negative velocities achieved in the eccentric phase of the self-paced condition necessitate a larger impulse to overcome the larger downward momentum. This is visible in Figure 2: the onset of the eccentric phase is marked by a steep unloading phase, followed by a large positive impulse before the onset of the concentric phase. Conversely, due to the much lower negative velocity in the 2-s condition, the positive impulse necessary to initiate the concentric phase was much smaller. Combined with a similar concentric phase duration in both conditions, this might have enabled the participant to reach faster concentric velocities in the 2-s condition across all external loads.

Another consequence of the negative momentum differences between the fast and slow conditions seems to be the timing of the peak vGRF. Under the self-paced instructions, the

peak vGRF coincides with the transition from the eccentric to concentric phase (± 10 ms) versus later in the concentric phase (± 90 ms from the onset) for the 2-s condition. This may suggest different kinetic strategies adopted under both conditions. The self-paced condition might have permitted better utilisation of the stretch-shortening cycle (SSC), which has been shown to augment force production at the onset of the concentric phase (McCarthy et al., 2012). The rapid acceleration combined with relatively high vGRF to overcome negative momentum might provide the musculotendinous unit with higher mechanical stretch for SSC utilisation (Fukutani, Kurihara and Isaka, 2015). On the other hand, the slower descent and eccentric forces in the 2-s eccentric phase condition might have impeded full application of SSC. Rather, the participant developed peak vGRF later in the concentric phase. This would have occurred with the knee and hip joints closer to 90°, which enables higher joint torque development compared to the higher joint angles of the bottom position (Marginson & Eston, 2001). Thus, not only do the eccentric phase instructions modulate peak vGRF and peak concentric velocity, but also the position of highest force generation.
The main limitation of the present case study is the sample size of just one participant, and the limited trials attempted to avoid fatigue affecting the peak vGRF. To confirm our preliminary findings, future studies should include a larger sample size, investigate more kinetic variables, and examine the effect of eccentric phase duration in different lower-body RT tasks. To expand on our findings, future studies should include measures of SSC, and examine how other variables (e.g., maximal strength, range of motion) affect the discrepancies of kinetic strategies between eccentric phase instructions.

CONCLUSION: This case study on a single participant showed that heavier external loads may lead to higher peak vGRF in the RFESS. Importantly, intentionally slowing down the eccentric phase seems to reduce peak vGRF, but could lead to higher concentric velocities due to lower negative momentum before the onset of the concentric phase. The distinction between maximising peak vGRF or peak concentric velocity may be important during both training and strength testing. These preliminary results may inform sports science practitioners and researchers of the importance of coaching instructions in RT movements.

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