

Original Article

# Force production during squats performed with a rotational resistance device under stable versus unstable conditions

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**Abstract.** [Purpose] Force production during a squat action on a rotational resistance device (RRD) under stable and unstable conditions. [Subjects and Methods] Twenty-one healthy males were asked to perform six sets of six repetitions of squats on an RRD on either stable or unstable surfaces. The stable and unstable sets were performed on different days. Muscular outputs were obtained from a linear encoder and a strain gauge fixed to a vest. [Results] Overall, the results showed no significant differences for any of the dependent variables across exercise modes. Force<sub>mean</sub> outputs were higher in the concentric phase than in the eccentric phase for each condition, but there were no differences in velocity, time or displacement. The force<sub>peak</sub> was similar in the eccentric and concentric phases of movement under both stable and unstable conditions. There were no significant differences in force<sub>mean</sub> between sets per condition or between conditions. [Conclusion] These results suggest that performing squats with a RRD achieves similar force<sub>mean</sub> and force<sub>peak</sub> under stable and unstable conditions. The force<sub>peak</sub> produced is also similar in concentric and eccentric phases.

**Key words:** Strength training, Accelerometer, Instability

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## INTRODUCTION

Instability in resistance training has gained increasing popularity as a component of sports training and musculoskeletal rehabilitation due to the growing evidence of its positive effects. Instability can be achieved by using free weights instead of machines<sup>1)</sup>, by reducing the number of contact points or the base of support<sup>2)</sup>, or by adding an unstable surface to the exercise<sup>3-5)</sup>.

To date, most studies have focused on the mechanical output of performing load resistance exercises on stable and unstable platforms with free weights. Moreover, the barbell squat exercise is often chosen because it strengthens and supports essential and necessary muscles for certain sports<sup>6, 7)</sup>. Overall, these studies have demonstrated force or power reductions when performing squat exercises under unstable conditions (versus stable conditions)<sup>8)</sup>, and have found that increasing the instability of the exercise decreases the external load<sup>9)</sup>. This effect is probably due to the greater effort required to maintain core stability.

Assessing the performance of squats under both stable and

unstable conditions, several authors have reported decreases in force outputs ranging from 83% to 18%, indicating a large magnitude of potential change<sup>8)</sup>. This demonstrates that there are large differences between exercises and instability devices. Therefore, the magnitude of effort will depend on the degree of instability caused by the devices and body positions. However, part of the research on which this argument is based involved only isometric exercises performed with free weights<sup>6, 10)</sup>. In another study, when dynamic exercises were performed on an unstable surface, force and power reductions were smaller<sup>11)</sup>.

Some of the studies also present methodological limitations. The examination of absolute intensity, for example, may result in higher relative loads for the unstable condition<sup>12-14)</sup> or fail to show normalized muscular outputs<sup>5, 6, 15)</sup>. Moreover, studies that assessed external mechanical outputs ignore the force and power necessary to move body segments. Without information on the specifics of the biomechanical model used and how force and power were calculated, readers do not know what muscular power variable is being discussed or how to compare the results against previous studies.

Recently, alternative methods of providing external resistance have been studied, particularly for use in microgravity environments<sup>16, 17)</sup>. One such modality is rotational resistance, which differs from more traditional forms by generating resistance as a function of the mass, the distribution of mass, and the angular acceleration of the flywheel, and thus offering resistance independent of gravity<sup>17)</sup>. Muscle

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activation and motor unit recruitment cannot be complete in the vast majority of repetitions executed in typical weight resistance exercise manoeuvres. In contrast, rotational resistance exercise (RRE) allows for accommodated maximal or near-maximal actions from the very first repetition of a set<sup>16, 18</sup>. Furthermore, weight resistance exercise employs a constant external load, which inevitably results in submaximal eccentric actions. Conversely, RRE could offer maximal voluntary concentric and eccentric resistance while performing exercises under unstable conditions.

Several studies have confirmed the efficacy of RRE for improving strength and power<sup>19, 20</sup>. Suitable devices for assessing RRE include the YoYo™ system (YoYo™ technology, Stockholm, Sweden) and the VersaPulley™ system (Portable VersaPulley™, Heard Rate Inc., Costa Mesa, CA). Only one study to date has compared joint kinetics between squats performed when using free weights versus the VersaPulley™, and it was performed under stable conditions<sup>21</sup>. To our knowledge, the production of relative force while performing heavy or maximal squat effort under both stable and unstable conditions using a rotational resistance device (RRD) has not been studied to date; it remains unresolved whether the unstable surfaces frequently used during athletic training and rehabilitation produce different forces from those generated using stable surfaces during exercises with a RRD.

This study aimed to compare force production during squat with an RRD under stable and unstable conditions. For this purpose, the dynamic squat movement was selected because it is one of the most widely performed exercises by athletes. The following hypotheses were proposed: (a) when performing squats with an RRD, force production would be lower under unstable than under stable conditions; (b) force production would be higher in the concentric phase than the eccentric phase of movement under each condition (stable and unstable); and (c) force production would decrease with successive sets.

## SUBJECTS AND METHODS

Twenty-one healthy male volunteers were recruited, all physical education students with previous experience of supervised resistance training (average 3 years), but not with an RRD or instability resistance training. Their (mean  $\pm$  standard deviation) age, height and weight were  $23.7 \pm 3.0$  years,  $1.80 \pm 0.8$  m and  $77.4 \pm 7.9$  kg, respectively. The one repetition maximum (1RM) test result for the back squat was  $112.6 \pm 19.2$  kg. Before testing, subjects were required to abstain from moderate-high intensity exercise, alcohol and caffeine for 12 hours. They received information about the procedures and the possible risks, and they were asked to provide consent before inclusion. The procedures were performed in accordance with the requirements of the Declaration of Helsinki and were approved by the local ethics committee.

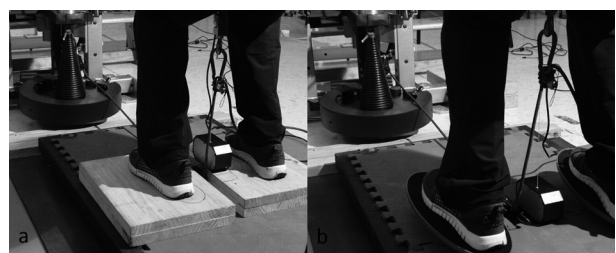
Prior to the study subjects underwent a familiarization session, during which the technique of the squat exercise with the RRD was explained. The procedure was performed using submaximal effort in the concentric phase as a practice. Emphasis was placed on proper technique, especially

when performed on the unstable surface. First, subjects took part in a standardized warm-up. They were then randomized to perform six sets of six repetitions of squats on the RRD (position 2 and 16 weights) under both stable and unstable (Pielaster, Biolaster, S.L. Guipúzcoa, Spain) conditions, using maximal effort in the concentric phase. Reliability scores were Intraclass correlation coefficient (ICC) = 0.97 and Coefficient of variation (CV) = 4.3%. A rest interval of 1 min was allowed between sets. Participants were tested on different days under stable and unstable conditions, with a minimum of 2 days between procedures. The results of the six repetitions of each set with and without instability were then evaluated.

The exercise mode required the trainee to wear an adjustable vest equipped with a carabiner. Feet were placed on both sides of the ground pulley at hip-width apart and a measure was marked on the floor to be maintained under both stability conditions. The squat was performed on a Pielaster and a stable wooden platform specifically designed to maintain the feet at the same height in both conditions (Fig. 1). Then, the RRD tether was tied to the vest through the gauge by carabiners. Finally, the tension of the tether was adjusted while maintaining both legs in extension. Flywheel rotation was initiated by winding the tether until it reached 90° of knee flexion on visual inspection. Thereafter, the participant initiated movement, progressively increasing the velocity until the third repetition, at which point maximal velocity was reached. Each repetition was conducted to stop at about a 90° knee angle. Verbal encouragement was provided throughout to ensure maximal effort and proper technique.

The RRD used in the current study (Byomedic System SCP, Barcelona, Spain) consists of a metal flywheel with a radius length of 0.21 m with 16 weights (0.410 kg each) located at the perimeter. A fixed axis is located at the centre of the beam, about which the weights rotate. A cone is attached above the flywheel, and as the flywheel and cone spin, a tether winds and unwinds around the cone. The length of the tether increases as it unwinds (concentric phase), and when it is completely unwound, the cone continues to spin and the tether begins to wind around the cone, thereby decreasing the total length (eccentric phase). This device offers the option of changing the speed/force ratio by modifying the position of the closer round pulley with respect to the cone (from position 1, for force, to position 4, for speed). The inertia of the device with 16 weights was  $0.27 \text{ kg} \cdot \text{m}^2$ .

The force production exerted on the RRD was measured by a strain gauge, and a linear encoder was used to measure



**Fig. 1.** Squat performed in a rotational resistance device under stable (a) and unstable (b) conditions

the vertical displacement of the subject (MuscleLab, Ergotest Technology AS, Langesund, Norway). The strain gauge and the tether of the linear encoder were attached to the vest by a carabiner. The linear encoder was positioned between the feet, close to the floor pulley. Data were sampled at a frequency of 100 Hz (time resolution, 10 ms) with an accuracy of 0.075 mm, recorded by an acquisition unit and stored on a portable computer equipped with the data acquisition and analysis program. The associated software (MuscleLab V8.27) displays the force, the time course of displacement and the velocity. This device has been widely used to evaluate dynamic muscle work, and good reliability scores have been reported<sup>22</sup>). Then, total force outputs exerted by the subject were calculated. To measure acceleration in the horizontal (X–Y) and vertical (Z) axes, a three-axis 10-g accelerometer (Mega Electronics Ltd., Finland) was fixed with adhesive tape at the top edge of the right Pielaster. This was connected to a 14-bit AD converter (ME6000 Biomonitor, Mega Electronics, Kuopio, Finland) and signals were sampled at a frequency of 2,000 Hz. The accelerometer was calibrated by two-point calibration with zero gravity and the earth's gravity of 1 G ( $9.81 \text{ m}\cdot\text{s}^{-2}$ ). The vector of the acceleration was computed by quadratic combination of the values of the X-, Y- and Z-axes.

Data analyses were performed using PASW Statistics for Windows, Version 18.0 (SPSS, Inc, Chicago, IL, USA). Statistically significant differences were fixed at  $p < 0.05$ . Model assumptions were validated by means of the Kolmogorov-Smirnov test of normality and Levene's test of equality of variances. The different response variables (force, velocity, time and displacement) were analysed by 3-way analysis of variance (ANOVA) with repeated measures. We used condition (stable and unstable), phase (concentric and eccentric) and set number (from 1 to 6), as well as their interactions, as

fixed factors. The subject was set as the random factor. All statistically non-significant interactions were removed from the model. When a statistically significant effect was found, we performed post-hoc comparisons with the Bonferroni correction method for multiple comparisons.

## RESULTS

Overall, the results showed no significant differences for any of the dependent variables across conditions (stable and unstable) (Table 1).

Force<sub>mean</sub> produced in the eccentric phase of the movement was lower (12.4%) than in concentric phase (Wald Chi-Square  $\chi^2 = 331.6$  and  $p < 0.001$ ) (Table 2). However, the interaction between condition and phase showed no significant differences ( $\chi^2 = 1.1$  and  $p = 0.313$ ). There were no differences in force<sub>peak</sub>, between phases and conditions. Nor there were significant differences in force<sub>mean</sub> between set number (from 1 to 6) under each condition (stable and

**Table 1.** Muscular outputs performing squat on RRD under stable and unstable conditions (n = 21)

Muscular outputs	Rotational Resistance Device (RRD)	
	Stable	Unstable
Force <sub>mean</sub> (N)	1501.1 ± 186.6	1468.2 ± 199.8
Force <sub>mean</sub> /bm (N·kg <sup>-1</sup> )	19.4±2.4	19.01±2.5
Velocity <sub>mean</sub> (m·s <sup>-1</sup> )	0.69 ± 0.09	0.70 ± 0.08
Time (s)	1.36 ± 0.08	1.37 ± 0.07
Displacement (m)	0.93 ± 0.06	0.94 ± 0.07

There were no significant differences. bm: body mass

**Table 2.** Muscular outputs between concentric and eccentric phases under stable and unstable conditions during a squat on a rotational resistance device (n = 21)

Phase	Muscular outputs	Rotational Resistance Device (RRD)	
		Stable	Unstable
Concentric	Force <sub>mean</sub> (N)	1602.5 ± 169.7	1563.8 ± 190.6
	Force <sub>mean</sub> /bm (N·kg <sup>-1</sup> )	20.8 ± 2.3	20.3 ± 2.5
	Force <sub>peak</sub> (N)	3012.1 ± 475.1	2922.5 ± 528
	Force <sub>peak</sub> /bm (N·kg <sup>-1</sup> )	39.1 ± 6.8	38 ± 7.4
	Velocity <sub>mean</sub> (m·s <sup>-1</sup> )	0.67 ± 0.09	0.68 ± 0.10
	Time (s)	0.69 ± 0.08	0.69 ± 0.08
	Displacement (m)	0.46 ± 0.06	0.47 ± 0.06
Eccentric	Force <sub>mean</sub> (N)	1400.4 ± 141.1*	1371.1 ± 160.9*
	Force <sub>mean</sub> /bm (N·kg <sup>-1</sup> )	18.1 ± 1.5*	17.7 ± 1.8*
	Force <sub>peak</sub> (N)	3074.3 ± 617.8	2941.4 ± 631.3
	Force <sub>peak</sub> /bm (N·kg <sup>-1</sup> )	39.9 ± 8.3	38.2 ± 8.7
	Velocity <sub>mean</sub> (m·s <sup>-1</sup> )	0.69 ± 0.07	0.69 ± 0.09
	Time (s)	0.67 ± 0.07	0.68 ± 0.07
	Displacement (m)	0.46 ± 0.06	0.47 ± 0.07

Values with \* are significantly different ( $p < 0.001$ ) between concentric and eccentric phases by Bonferroni test. Velocity in the eccentric phase of the movement showed as positive values (n = 21). bm: body mass

unstable separately) or between the two conditions.

The quadratic combination of the acceleration of the right Pielaster was  $3.43 \pm 1.08 \text{ m}\cdot\text{s}^{-2}$ . Figure 2 shows the acceleration of one subject recorded at the X-, Y- and Z-axes while performing six repetitions in the first set.

## DISCUSSION

This study compared force production on a RRD during squats performed under stable and unstable conditions. The first hypothesis of the study was not borne out, since there was a marked similarity in force output during the squat under both conditions.

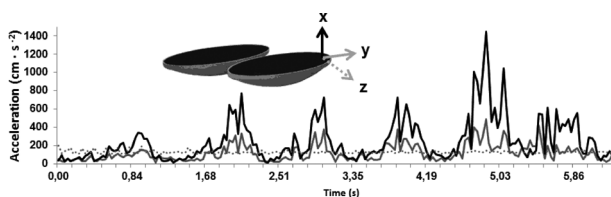
Several authors have reported that force and power output decrease with increasing instability<sup>8)</sup>. The discrepancy between the current study and those previous investigations may be attributable to the type of muscle action (isometric versus anisometric), the degree of instability during the recorded task (inflatable balance disc, Bosu<sup>®</sup> ball, balance cone, or foam blocks and Pielaster), and the equipment used (free weights, Olympic bar or RRD). Some studies also present methodological limitations, since they either examined absolute intensity<sup>12–14)</sup> or failed to show normalized muscular outputs<sup>5, 6, 15)</sup>. Moreover, previous research has often focused on external mechanical power and has ignored the force and power involved in moving the body segments. Finally, because the majority of these studies did not report all the specifics about the measured force, their findings need to be analysed with care.

A few studies have investigated maximal force or power production during squat manoeuvres on stable and unstable surfaces. Indeed, unstable surfaces, such as foam blocks and Bosu<sup>®</sup> balls, were used in a weight resistance squat exercise during which decreases were recorded in concentric force-peak, velocity-peak and power-peak, as well as range of motion and eccentric power-peak<sup>23)</sup>. Other research has examined power-mean in the concentric phase of squats when performing six sets of eight repetitions at 70% of 1RM<sup>7)</sup>, and showed significantly lower power-mean outputs when performing a resistance exercise on a Bosu<sup>®</sup> ball than on a stable support base. Similarly, power-mean was lower in the concentric phase of the squat manoeuvre with and without countermovement on a Bosu<sup>®</sup> ball while lifting different weights<sup>24)</sup>. Saeterbakken et al.<sup>6)</sup> noted the effect of different levels of instability on force output in isometric squats using two nonelastic straps. The force output using a power board was similar to that under the stable condition (–7%), but lower than for

a Bosu<sup>®</sup> ball (–19%) and a balance cone (–24%). The two nonelastic straps attached between the Olympic bar and the floor produced similar body stabilization using a power board (–7%); however, the force output with the RRD and Pielaster was lower (–2%).

There may be a simple explanation for the differences in force obtained between these studies. Performing squats creates an inverted pendulum, in which the subject's stabilization can be simplified as a standing rigid body with a mass, his/her mass centre height is above the ground and the rotational inertia with respect to the mass centre. In the standing posture, the mass centre height will be lower when performing a squat on the RRD than when squatting with the nonelastic straps. This greater stability could therefore partly explain the differences in force obtained. However, it should be stressed that the two studies compared different types of muscular action and used different models to calculate force production. For example, force-mean in a stable isometric squat was  $749 \pm 222 \text{ N}$ , notably lower than in the current study ( $1501 \pm 186 \text{ N}$ ); this is because it corresponds to the force obtained from the force cells, neglecting the total force performed by the subject. Furthermore, to our knowledge, this is the first study to compare force production during the squat manoeuvre on an RRD under stable and unstable conditions. Thus, no clear comparisons with previous studies can be made.

The Pielaster imposed a local degree of instability at the ankle, mainly in the X and Y axes, made the task more difficult than in the stable condition. However, it is assumed that the vertical tension of the tether attached close to the centre of gravity could have helped the subject to maintain similar body equilibrium under the two conditions. Therefore, the poor reduction of force-mean may be attributable to the relatively low biomechanical and neuromuscular challenges imposed on the trunk. Behm et al.<sup>11)</sup> stated that the degree of instability during the recorded task may be associated with the degree of force reduction. In the current study, the squat performed with RRD under unstable conditions would have produced a negligible degree of instability (–4%) in addition to the instability produced by the Pielaster (acceleration quadratic combination,  $3.43 \pm 1.08 \text{ m}\cdot\text{s}^{-2}$ ). There were few postural reactions or anticipatory postural adjustments when balancing on the Pielaster, possibly because the supplementary stabilization of the body produced by the tether compensated for the ankle instability. Hence, the unstable squat used in this study suggests that different local and global demands are produced by instability. Note also that the arms were fixed on the body while performing the squat on the RRD under stable and unstable conditions to prevent anticipatory postural adjustments. Unstable surfaces create pressure and tension around the ankle joint stimulating the mechanoreceptors, thus generating afferent stimuli and reflexive motor responses which increase joint stability. Surfaces such as the Pielaster may be ideal for stimulating these mechanoreceptors and may help in the prevention of (or recovery from) a range of joint injuries<sup>25)</sup>. To activate the vastus medialis oblique, and to enhance the vastus medialis oblique/vastus lateralis ratio in order to prevent or mitigate knee joint dysfunction (the patellofemoral pain syndrome) highly unstable surfaces should be selected<sup>26)</sup>.



**Fig. 2.** Acceleration obtained in the right Pielaster at the X-, Y- and Z-axis during six repetitions of the first set in one participant

As expected, there were differences in force<sub>mean</sub> between the concentric and eccentric phase of the movement under each condition. Maximal force<sub>mean</sub> production occurred in the concentric phase under stable (12.6%) and unstable (12.3%) conditions. Once the concentric phase was completed, the tether rewound onto the shaft by virtue of the kinetic energy of the rotating flywheel. The subsequent eccentric muscle action was executed by resisting the pull of the tether, aimed at bringing the flywheel to a stop at a knee angle of about 90°. Due mainly to mechanical friction, a lower force<sub>mean</sub> was reached in the eccentric than in the concentric phase under both stable (1602.54 N vs. 1400.44 N) and unstable (1563.85 N vs. 1371.10 N) conditions. The friction produced while the tether wound and unwound around the cone converted kinetic energy into heat. The consequence of this friction was an evident tether degradation over successive repetitions, and in fact the tether had to be replaced during the study.

For their part, the two pulleys used also produced mechanical friction. During the concentric phase, the overall mechanical friction increased the necessary force applied by the subjects to rotating the flywheel, whereas the coefficient of friction in the eccentric phase decreased the overall effort of the subject to stop the flywheel. However, the force<sub>peak</sub> was slightly higher in the eccentric phase of the movement under both stable and unstable condition (2.1% and 0.6% respectively). Using a seated flywheel resistance device (YoYo® Technology, Stockholm, Sweden) under stable and unstable conditions, Norrbrand et al. (2008) reported lower force<sub>mean</sub> (8.8% vs. 12.6% respectively) and higher force<sub>peak</sub> (6.5% vs. 12.3% respectively); however, the force production was lower. The main reasons for these discrepancies are the mode of exercise and the different devices and moments of inertia used (YoYo®, 0.11 kg m<sup>-2</sup> and RRD 0.27 kg m<sup>-2</sup>). This finding should be taken into account when resistance exercises are implemented with RRD, particularly for training that requires the production of maximal force in the eccentric phase of movement. Therefore, it may be assumed that the muscle action of the subjects during the eccentric phase was executed by resisting the pull of the tether above all in the last third of the action, compensating for the loss of kinetic energy of the rotating flywheel in the eccentric phase.

The levels of eccentric force<sub>peak</sub> generated, similar to those produced in the concentric phase in both stable and unstable conditions, may potentially serve to prevent muscular strain. The protective effect of eccentric exercise on the occurrence of muscular strain injuries has already been reported in the literature<sup>27)</sup>. Askling et al. examined the effects of pre-season hamstring strengthening incorporating concentric and eccentric overload, and reported that this technique resulted in a significantly lower number of injuries compared with the control group. Given that muscular strains commonly occur during the eccentric phase of muscle action<sup>28–30)</sup>, overloading these muscles with eccentric training under stable and unstable conditions could potentially serve to prevent these injuries.

In contrast, we found that force production did not decrease over the sets under either stable or unstable conditions. In contrast to free weights, the inherent feature of RRD is that subjects perform maximal or near-maximal voluntary force

throughout each repetition of a set<sup>31)</sup>. Surprisingly, however, the rest time of 1 min between sets in the current study was sufficient to maintain a similar force<sub>mean</sub> over the sets under both stable and unstable conditions. When assessing this finding, we must bear in mind that the average duration of the effort of each set was brief, less than ten seconds in all cases. Nevertheless, it has been suggested that the ability to repeat high intensity efforts is an important determinant of fitness in several sports, and that neuromuscular factors are likely to be among the key elements involved. Among other variables, the intensity, number of sets, number of repetitions and the length of rest intervals are equally important factors that determine the training stimuli and the consequent force- and velocity-specific adaptations. These facts must be taken into account when squats are performed with an RRD as part of a training programme.

Our findings indicate that performing squats with an RRD achieves similar force<sub>mean</sub> in stable and unstable conditions. The force<sub>peak</sub> produced is also similar in concentric and eccentric phases. This exercise may be specially indicated for team sport players who need to improve strength and proprioception. It could also be included as part of injury prevention programmes for muscular lesions, ankle and knee joint injuries and low back pain. Moreover, it would avert the current need to place free-weights on the back, which would be of particular interest for certain athletes (e.g. taller basketball players) or other populations such as the young and the elderly. However, further research is needed to establish the benefits of each approach for preventing injuries and for improving core stability and balance. In addition, research is needed to compare the effectiveness of training with an RRD under stable and unstable conditions for enhancing specific performance tasks.

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