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# Introduction of dynamic rate-of-force development scaling factor in progressive drop jumps

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ABSTRACT

Rapid force generation across submaximal levels has been evaluated with the rate of force development scaling factor (RFD-SF) in different isometric tasks, while such measurement was still not verified in dynamic tasks. Our study was designed to evaluate the feasibility of the RFD-SF in dynamic drop jump (DJ) task ($RFD\text{-}SF_{DJ}$). A total of 55 young athletes performed isometric plantarflexion at different submaximal intensities and 60 DJs (6 different drop heights). For each participant we calculated linearity ($r^2$) and slope in isometric task ($RFD\text{-}SF_{PF}$), eccentric part of DJ ($RFD\text{-}SF_{DJ\text{-}ECC}$) and concentric part of DJ ($RFD\text{-}SF_{DJ\text{-}CON}$), as well as average jump height ($DJ_H$) from each drop height. Our results revealed strong linear force-RFD relationship for isometric plantarflexion ($r^2 = 0.90 \pm 0.06$), eccentric ($r^2 = 0.87 \pm 0.09$) and concentric phase of DJ ($r^2 = 0.80 \pm 0.18$). Significant moderate positive correlations were calculated between $RFD\text{-}SF_{PF}$ and $RFD\text{-}SF_{DJ\text{-}ECC}$ ($r = 0.311$, $p < 0.05$) and small negative correlations between $RFD\text{-}SF_{DJ\text{-}CON}$ and RFD-SF ($r = -0.276$, $p < 0.05$). Significant positive moderate correlations were seen only between $RFD\text{-}SF_{DJ\text{-}ECC}$ and $DJ_H$ from 10 cm ($r = 0.459$, $p < 0.001$) and 15 cm ($r = 0.423$, $p < 0.01$). This is the first study to introduce and confirm that $RFD\text{-}SF_{DJ}$ can be obtained from the multi-joint tasks (60 jumps) and still provide acceptable reliability and linear relationship. Furthermore, $RFD\text{-}SF_{DJ}$ may have greater practical application than RFD-SF assessed under the isometric conditions. This verification of $RFD\text{-}SF_{DJ}$ opens opportunities for further research regarding its practical application.



## 1. Introduction

The quality of movement initiation and the quickness of force production with the rate of force development scaling factor (RFD-SF) has been introduced in the past few years and used as a method in different studies concerning sports (Boccia et al., 2018), aging (Bellumori et al., 2013; Gurjão et al., 2009) disease (Uygur et al., 2020) and others. RFD-SF measure reflects neural and neuromuscular factors which quantify the quick force production across different submaximal force amplitudes, while maximal rate of force development (RFD) is relevant only for maximal contractions. Moreover, this measure is mathematically independent of strenght (unit /s) that allows simple comparison between individuals and muscle groups (Bellumori et al., 2011). The protocol, reliability and methodological considerations for RFD-SF assessment are already established in the literature (Bellumori et al., 2011; Djordjevic and Uygur, 2017) which enables comparison between different studies and muscle groups.

For RFD-SF assessment the subject needs to perform a series of fast isometric contractions to different submaximal target forces. This allows the calculation of the slope of the regression line between the peak values of the force pulses and their corresponding peak RFD at different submaximal intensities (Bellumori et al., 2011). For reliable results, it has been suggested that the subject performs approximately 100–125 fast contractions (ICC = 0.8 – 0.92), across different ranges of contraction intensities (20%, 40%, 60% and 80% of maximal voluntary contraction (MVC)), while acceptable reliability can be achieved with even smaller number of pulses (>50, ICC = 0.7) (Bellumori et al., 2011). Using this methodologically well-defined protocol, several studies reported RFD-SF as a reliable method for assessing neuromuscular quickness of different muscle groups (index finger, elbow extensors,

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knee extensors, different hip muscle groups) (Bellumori et al., 2011; Casartelli et al., 2014; Djordjevic and Uygur, 2017; Mathern et al., 2019).

To date, RFD-SF of different joints (i.e. the muscle groups) was measured only in isometric tasks. Some previous studies are suggesting that isometric force properties are importantly related to dynamic performance (Haff et al., 2005; Viitasalo and Aura, 1984), while others reported no significant relationships between the two (Murphy and Wilson, 1996; Wilson et al., 1995). One important factor which may influence this relationship is the joint addressed. Namely, biomechanical studies have clearly shown that the knee extensors and particularly ankle plantar flexors are dominant muscles in dynamic activities such as drop jump (DJ), especially during the take-off phase (Alkjaer et al., 2013). However, to our knowledge, no protocol aimed to assess RFD-SF under dynamic conditions. Thus, we considered that besides the evaluation of the rapid force generation of different intensities under isometric conditions, RFD-SF might also be evaluated under highly dynamic conditions, such as DJs ($RFD\text{-}SF_{DJ}$). Because DJ can be divided into the eccentric and concentric phase of the jump, we evaluated RFD-SF for both phases ($RFD\text{-}SF_{DJ\text{-}ECC}$, $RFD\text{-}SF_{DJ\text{-}CON}$). Specifically, progressive DJs from different heights can represent different submaximal intensities for each participant. Therefore, a greater number of DJs at different drop heights could hypothetically allow us to calculate the slopes of the regression line for this dynamic activity in a similar manner as in RFD-SF under isometric tasks.

The fundamental goal of our study was to verify the calculation of $RFD\text{-}SF_{DJ}$ and to compare its characteristics to previously established isometric RFD-SF (linear relationship between peak RFD and peak F). In case of verification, RFD-SF in dynamic condition may have greater practical implication compared to isometric test. Specifically, the first aim of this study was to introduce $RFD\text{-}SF_{DJ}$ in a multi-joint task such as ankle-dominant DJs from different drop heights, and to verify its linearity compared to the plantar flexors isometric task ($RFD\text{-}SF_{PF}$). We hypothesised that the regression line calculated from progressive DJs will have an acceptable linearity in both phases of jump ($r^2 > 0.70$). The second aim of the study was to investigate the relationship between $RFD\text{-}SF_{DJ\text{-}ECC}$/$RFD\text{-}SF_{DJ\text{-}CON}$ and $RFD\text{-}SF_{PF}$. We hypothesised that $RFD\text{-}SF_{DJ}$ of both phases and $RFD\text{-}SF_{PF}$ will be significantly correlated. Finally, the third aim was to evaluate the relationship between both phases of $RFD\text{-}SF_{DJ}$, $RFD\text{-}SF_{PF}$ and average DJ height ($DJ_H$), where we hypothesised that $RFD\text{-}SF_{DJ}$/$RFD\text{-}SF_{PF}$ will have a significant positive correlation with $DJ_H$. This assessment will verify the use of dynamic $RFD\text{-}SF_{DJ}$ and its associations with isometric task which involves similar muscle groups.

## 2. Methods

### 2.1. Participants

A total of 55 young healthy athletes from volleyball (14), soccer (14), track and field (14), basketball (9) and tennis (4) were included in the study (Table 1). Self-reported take-off leg during unilateral jumping movements was considered as dominant side. The participants were asked to refrain from physical activities at least 48 h before testing. Participants with previous lower leg injuries (past 6 months), neurological disorders, low back pain or recent general illness were excluded from the study. Participants and their parents/guardians (in case they were under the age of 18) were informed about the testing procedures and provided written informed consent prior to commencing the study. The experiment was approved by the Slovenian Medical Ethics Committee (approval no. 0120–99/2018/5) and was in accordance with the Declaration of Helsinki.

#### 2.1.1. Procedures

Participants first performed a 10-min warm-up (5 min of light running, 4 min of dynamic stretching and 1 min of activation exercises). Afterward, they performed isometric plantarflexions against a dynamometer (Fig. 1a) and DJs from different drop heights (Fig. 1b). The order of the two tasks was randomized.

#### 2.1.2. Materials and testing

Plantarflexion MVC and $RFD\text{-}SF_{PF}$ were assessed while participants were seated in a chair of the isometric ankle dynamometer (S2P, Science to Practice, ltd., Ljubljana, Slovenia) (Fig. 1, a). Even though values from dynamometer represent torque, we used $RFD\text{-}SF_{PF}$ expression as its values in scaling factor are independent of how they are calculated. The dynamometer was adjusted to the participant, so ankles, knees, and hips were at 90°. Both feet were fixed on the mechanically independent pedals. The axis of each pedal was aligned with the lateral malleolus. Heel rising was prevented with rigid mechanical brakes over the knees, while tightly fastened rigid straps were placed over the dorsum of each foot at the level of the metatarsophalangeal joints. Each participant performed three MVCs in against a dynamometer for unilateral (dominant) plantarflexion with 60 s of rest between each MVC. They were instructed to gradually increase their force and push as hard as possible in the direction of plantarflexion. Contractions were sustained for ~ 3 s, meanwhile, verbal encouragement was given to the participant. Maximal force ($F_{MVC}$) from 3 repetitions was calculated and considered for further analysis. Following MVC, the $RFD\text{-}SF_{PF}$ relationship for (dominant leg) was assessed as all previous RFD-SFs were measured unilaterally (Bellumori et al., 2013, 2011; Casartelli et al., 2014; Djordjevic and Uygur, 2017; Uygur et al., 2020). Firstly, participants were asked to complete about 10–15 submaximal contractions for familiarization purposes so they could perform pulses as instructed (produce explosive force pulses using toes-down action against the rigid fixation – produce the force as quickly as possible and relax immediately). Then, they completed sets of 20–25 explosive isometric contractions at 20%, 40%, 60% and 80% of $F_{MVC}$ that followed in random order. The number of pulses was selected based on previous results (Bellumori et al., 2011). Each pulse was cued by the experimenter with the verbal command ("go") approximately 4–5 s apart. Participants were encouraged to focus on explosive performance while they were instructed to keep the peak of the force burst at about the target value indicated on the screen (secondary goal), not stressing the precision really, as it has been shown that it slows rate of force production (Gordon and Ghez, 1987). Altogether, approximately 100–125 fast contractions were assessed across the range of contraction intensities. The target force was displayed as a horizontal line on the graph on a computer screen placed at the eye level

**Table 1**
Characteristics of the participants.

| Gender | Number | Age (years) | Body height (cm) | Body mass (kg) | BMI | Left dominant | Right dominant |
|---|---|---|---|---|---|---|---|
| Female | 7 | 14.6 ± 1.1 | 167.7 ± 5.6 | 53.9 ± 4.4 | 19.2 ± 1.6 | 5 | 2 |
| Male | 48 | 15.2 ± 0.9 | 179.0 ± 6.9 | 67.0 ± 9.2 | 20.8 ± 2.0 | 29 | 19 |
| All | 55 | 15.1 ± 1.0 | 177.6 ± 7.6 | 65.3 ± 9.7 | 20.6 ± 2.1 | 34 | 21 |

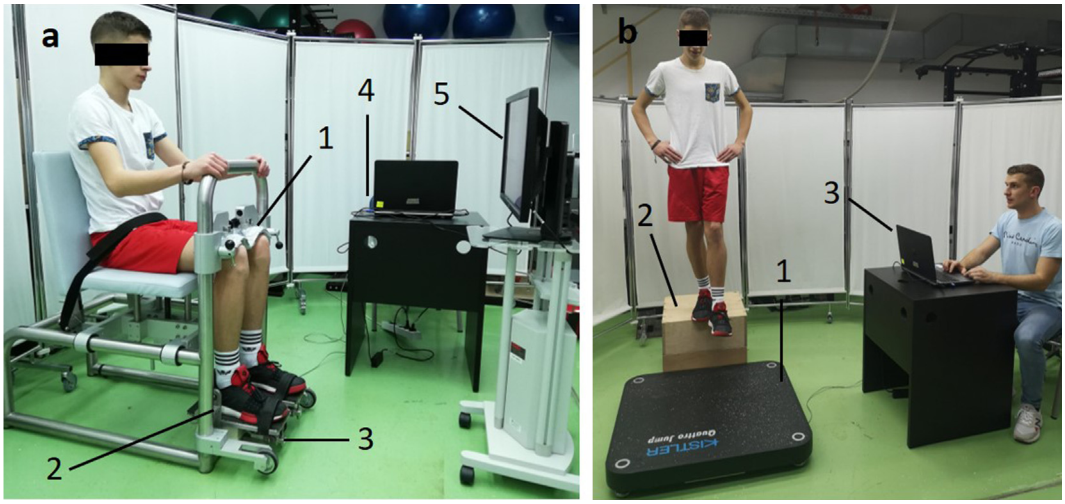


**Fig. 1.** Measurement set-up. a) Subject in the isometric ankle dynamometer: 1 – ankle motion restrictors, 2 – foot pedals with the rigid straps, 3 – strain gauge sensors, 4 – acquisition and analogue-to-digital conversion unit, 5 – monitor for visual feedback. b) Subject in starting position for drop jump: 1 – Quattro Jump plate, 2 – wooden cubes for height jump adjustment, 3 – acquisition and analogue-to-digital conversion unit.

(Fig. 1a). Participants rested for 60 s between different $\%F_{MVC}$ intensities.

In the second task participants performed 10 bilateral DJs on the force plate (Quattro Jump, Kistler, model 9290DD, Winterthur, Switzerland) from each of the six different drop heights (10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm) (Fig. 1b). In previous pilot study we concluded that most participants could perform proper DJs (DJ contact time around 180 ms or less, no heel contact, parabolic shape of the ground reaction force (GRF):time curve) from drop heights up to 35 cm. Order of drop heights was randomized. Participants were instructed to "step out" from the box with one foot and tip over the standing leg without lowering your centre of mass or jumping up, jump as fast and high as possible, stressing the short contact time and avoiding the heels touching the ground. The rest between the consecutive DJs was 30 s and between the consecutive sets of jumps from different heights was 2 min.

### 2.1.3. Data acquisition and analysis

The signals from the ankle dynamometer force transducers (1-Z6FC3/200 kg, Hottinger-Baldwin Messtechnik GmbH, Darmstadt, Germany) as well as those from the force plate were sampled at 1,000 Hz and low pass filtered (Butterworth 2nd order). Data were acquired and processed using custom-made LabView 2015 routines (National Instruments Corp., Augustin, Texas, USA) and commercially available software (Kistler MARS by S2P, Winterthur, Switzerland), for the dynamometry and force plate signals respectively. Signals were filtered with 5 Hz cut-off frequency while RFD was calculated as a peak value of derivate of the force curve (Djordjevic and Uygur, 2017; Maffiuletti et al., 2016). Data were processed by a single investigator in custom software (LabView 2015, National Instruments Corp., Augustin, Texas, USA). Isometric plantarflexion signals that deviated from the baseline before the contraction, or that had double peaks, and inappropriate relaxation phase were excluded from further analysis. In case when it was obvious that DJ was not performed properly, the DJ was repeated. Moreover, DJs exclusion was applied for signals with contact time above 200 ms or signals with heel strike (1.5% of signals was rejected).

The regression parameters were obtained from the relationship between the peak force and the corresponding peak RFD. For each participant, we calculated the selected parameters from the plantarflexion isometric force pulses and from the DJs force plate signals. Based on force plate signal acquired before the first touch of the toes and a steady-state period after the landing (2–3 s), force plate signals were divided into the eccentric and concentric phase of the DJ with help of the equation:

$$\int_{Start}^{x}[F(t)-BW(t)]dt \geq \int_{Start}^{Steady}[F(t)-BW(t)]dt$$

where F is a vertical force, BW is body weight of the subject, t is time, Start [s] indicates the beginning of the DJs contact phase, and Steady indicates the event when the force becomes steady after the landing (Fig. 2), which is defined as the beginning of the first 1-s interval after the final landing on which Min(F(t)) and Max(F(t)) are between BW − 10N and BW + 10N respectively. According to the above function, the algorithm finds the smallest x that satisfies the above condition; the beginning of the push-off is *x*. Based on that we calculated the slope of the regression line (i.e., $RFD\text{-}SF_{PF}$, $RFD\text{-}SF_{DJ\text{-}ECC}$, $RFD\text{-}SF_{DJ\text{-}CON}$) which quantifies the magnitude of the ability to scale RFD with the magnitude of force produced. We obtained $r^2$ from the regression relation between peak F and RFD which reveals consistency and linearity of the regression line. Similar to previous studies (Bellumori et al., 2013; Mathern et al., 2019) we excluded y-intercepts of the regression lines as it receives little attention in RFD-SF literature.

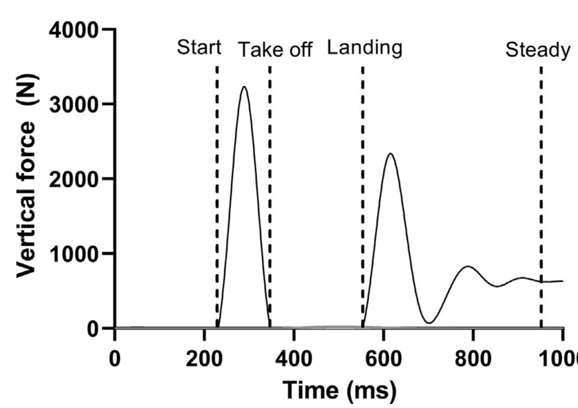


**Fig. 2.** Representative figure of the force plate signal used for calculation of the drop jump parameters.

#### 2.1.4. Statistical analysis

Descriptive data of the dependent variables are presented as means and standard deviations. Normal distribution of the data was investigated with the Shapiro-Wilk test. $DJ_H$ was calculated for each DJ drop height. Reliability was assessed through intraclass correlation coefficient (ICC), standard error of measurement (SEM) and coefficient of variation (CV) (Weir, 2005). For each drop height we split data on halves (5 jumps from each drop height for data set 1 and other 5 jumps for each drop height for data set 2, random selection). From each of the two dataset halves, $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{DJ\text{-}CON}$ were calculated for reliability assessment. The values of ICC were interpreted as: < 0.5 indicate poor reliability, 0.5–0.75 indicate moderate reliability, 0.75–0.9 indicate good reliability, and > 0.90 indicate excellent reliability (Koo and Li, 2015). Qualitative interpretations of the r coefficients as defined by Hopkins et al. (2009) (0.00–0.19 trivial; 0.20–0.29 small; 0.30–0.49 moderate; 0.50–0.69 large; 0.70–0.89 very large; 0.90–0.99 nearly perfect; 1.00 perfect) are provided for all significant correlations. All statistical analyses were performed using the SPSS (IBM SPSS version 25.0, Chicago, IL, USA) software package with statistical significance set at an alpha level of 0.05 (two-tailed).

## 3. Results

Excellent reliability and acceptable CV and SEM were obtained for the newly introduced $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{DJ\text{-}CON}$ (Table 2).

Our results indicated a strong linear relationship between peak forces and their corresponding RFD obtained from the DJs in the eccentric ($r^2$ = 0.87 ± 0.09) and concentric phase ($r^2$ = 0.80 ± 0.18). Representative sample recording of force pulses during DJs is presented in Fig. 3a, while plots (eccentric and concentric phase) with peak forces and their corresponding RFD of the progressive DJs (normalised based on DJ with highest peak F ($\%F_{max}$) and peak RFD ($\%F_{max}$/s)) are presented on Fig. 3b and 3c. The average $RFD\text{-}SF_{DJ\text{-}ECC}$ (ascending part of GRF curve) was 12.6 ± 2.2 /s, while $RFD_{DJ\text{-}CON}$ (descending part of GRF curve) was −11.3 ± 2.3 /s. Representative sample recording of force pulses during isometric plantarflexion and plot are presented in Fig. 3d and Fig. 3e. Obtained regression line linearity for isometric plantar flexion was strong ($r^2$ = 0.90 ± 0.06), while the average $RFD\text{-}SF_{PF}$ for isometric plantarflexion task was 6.0 ± 1.1 /s. RFD values for each drop height in drop jumps and each $F_{MVC}$ target level in isometric plantarflexion are presented in Table 3.

Significant moderate positive correlations were observed for $RFD\text{-}SF_{PF}$ and $RFD\text{-}SF_{DJ\text{-}ECC}$ (r = 0.311, $p < 0.05$), while small negative correlations were calculated between $RFD\text{-}SF_{PF}$ and $RFD\text{-}SF_{DJ\text{-}CON}$ (r = -0.276, $p < 0.05$). Very large negative associations were calculated for $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{DJ\text{-}CON}$ (r = −0.837, $p < 0.001$).

Associations between $RFD\text{-}SF_{DJ\text{-}ECC}$, $RFD\text{-}SF_{DJ\text{-}CON}$, $RFD\text{-}SF_{PF}$ and $DJ_H$ are presented in Fig. 4. In general, significant correlations between $RFD\text{-}SF_{DJ\text{-}ECC}$ and $DJ_H$ from lower drop heights (10–20 cm) were small to moderate (r = 0.298–0.459, p < 0.001–0.05), while

**Table 2**
Reliability values for $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{DJ\text{-}CON}$.

| | Mean 1 ± SD | Mean 2 ± SD | $ICC_2$ (95% CI) | CV (95% CI) | SEM | p |
|---|---|---|---|---|---|---|
| $RFD\text{-}SF_{DJ\text{-}ECC}$ (/s) | 12.5 ± 2.3 | 12.6 ± 2.6 | 0.91 (0.77, 0.96) | 5.6 (4.0, 9,3) | 0.7 | 0.79 |
| $RFD\text{-}SF_{DJ\text{-}CON}$ (/s) | −10.9 ± 3.9 | −10.9 ± 2.6 | 0.94 (0.83, 0.97) | −7.7 (-5.5, −12.7) | 0.8 | 0.57 |

SD – standard deviation, ICC (95% CI) - Interclass correlation coefficient (95% confident interval), CV – Coefficient of variation, SEM – standard error of measurement, p – p value.

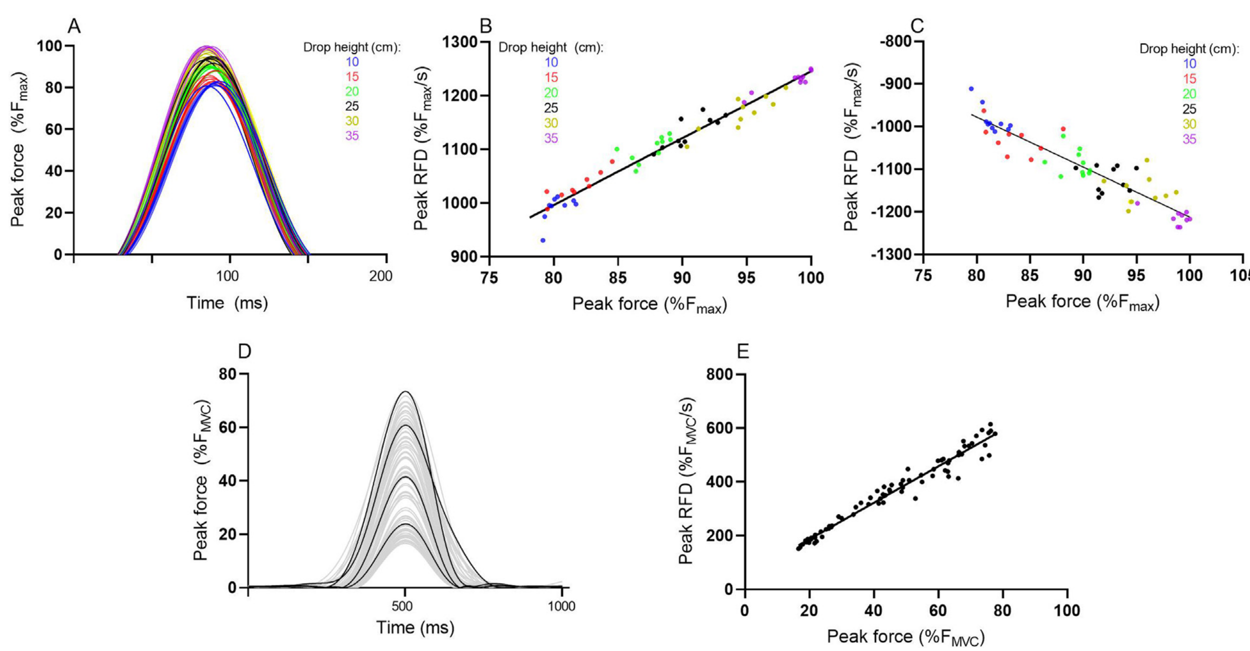


**Fig. 3.** Representative subject: a) sample recording of force pulses from progressive drop jumps (DJ); b) rate of force development scaling factor (RFD-SF) plot with data points taken from the peaks of the eccentric phase ($RFD\text{-}SF_{DJ\text{-}ECC}$) in progressive DJs; c) RFD-SF plot with data points taken from the peaks of the concentric phase ($RFD\text{-}SF_{DJ\text{-}CON}$) in progressive DJs; d) sample recordings of rapid force pulses to a variety of amplitudes in the isometric plantarflexion task ($RFD\text{-}SF_{PF}$) ; e) RFD-SF plot with data points taken from the peaks of the isometric plantarflexion task ($RFD\text{-}SF_{PF}$).

**Table 3**
RFD values for each drop height in drop jumps (eccentric and concentric phase) and for each torque target level in isometric plantarflexion.

| | Drop jumps | | Isometric plantarflexion | |
|---|---|---|---|---|
| Drop height (cm) | Eccentric RFD ($10^2$N/s) | Concentric RFD ($10^2$N/s) | Submaximal level | RFD (Nm/s) |
| 10 | 316.31 ± 59.38 | −319.40 ± 55.59 | 20% $F_{MVC}$ | 186.7 ± 20,1 |
| 15 | 336.84. ± 59.30 | −333.59 ± 59.03 | 40% $F_{MVC}$ | 328.2 ± 31.2 |
| 20 | 348.50 ± 61.27 | −346.51 ± 60.04 | 60% $F_{MVC}$ | 448.3 ± 51.2 |
| 25 | 366.94 ± 63.41 | −361.73 ± 63.23 | 80% $F_{MVC}$ | 516.3 ± 68.5 |
| 30 | 380.90 ± 65.85 | −374.00 ± 65.44 | | |
| 35 | 391.07 ± 68.32 | −382.00 ± 68.20 | | |

RFD – rate of force development (in isometric plantarflexion the values actually represent rate of torque development, but because of consistency RFD term is used), $F_{MVC}$ – maximal force.

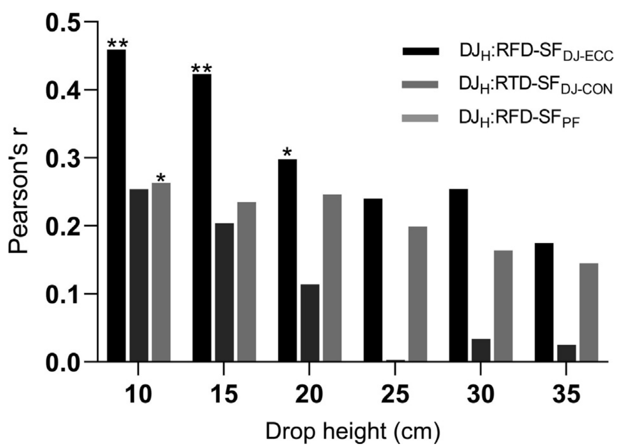


**Fig. 4.** Pearson correlations between: i) average drop jump height ($DJ_H$) and slope of eccentric phase of regression line in drop jump (DJ) task ($RFD\text{-}SF_{DJ\text{-}ECC}$); ii) $DJ_H$ and slope of concentric phase of regression line in DJ task ($RFD\text{-}SF_{DJ\text{-}CON}$); iii) $DJ_H$ and slope of regression line in isometric plantar flexion task ($RFD\text{-}SF_{PF}$). **statistical significance, $p < 0.01$; *statistical significance, $p < 0.05$.

correlations between $RFD\text{-}SF_{DJ\text{-}ECC}$ and $DJ_H$ from higher drop heights (25–35 cm) did not reach statistical significance (r = 0.175–254, p = 0.06–0.20). There were no significant correlations between $RFD\text{-}SF_{DJ\text{-}CON}$ and $DJ_H$ (r = -0.253 – 0.003, p = 0.063–0.854). Correlations between $RFD\text{-}SF_{PF}$ from isometric plantarflexion task and $DJ_H$ were positive to small and either significant/close to significant for lower drop heights (10, 15 and 20 cm, r = 0.235–0.263, p = 0.05, p = 0.07, p = 0.08 respectively) or not significant (25–35 cm, r = 0.1 45–0.199, p > 0.145).

## 4. Discussion

This study was designed to evaluate the feasibility of the RFD-SF in dynamic DJ task. The results with respect to the dynamic RFD-SF revealed: 1) strong linear relationship in both phases of DJ ($r^2$ = 0.80 – 0.87) that allow us to introduce the measurement of $RFD\text{-}SF_{DJ}$; 2) statistically significant moderate positive correlations between $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{PF}$ and small negative associations between $RFD\text{-}SF_{DJ\text{-}CON}$ and $RFD\text{-}SF_{PF}$; 3) $DJ_H$ from 10 cm has a significant positive small correlation with $RFD\text{-}SF_{PF}$ and moderate positive correlation with $RFD\text{-}SF_{DJ\text{-}ECC}$, while $DJ_H$ from 15 cm and 20 cm has a significant positive small to moderate correlation only with $RFD\text{-}SF_{DJ\text{-}ECC}$.

To our knowledge, this is the first study that explored $RFD\text{-}SF_{DJ}$ from the multi-joint tasks such as progressive DJs. Our results clearly showed that it is possible to measure $RFD\text{-}SF_{DJ}$ in dynamic conditions (acceptable reliability) which confirms our first hypothesis. In isometric plantarflexion task intensity of submaximal explosive contractions is regulated based on $F_{MVC}$. Meanwhile, the intensity of DJs was increased by raising the drop height, as it was shown as a more effective way to manipulate the intensity of the jumps compared to increasing load from the same height (Makaruk and Sacewicz, 2011). $RFD\text{-}SF_{PF}$ protocol demands a greater number of explosive contractions to achieve satisfying linearity (Bellumori et al., 2011). Likewise, a greater number of DJs from different drop heights are needed to obtain the target outcome parameters. In our case regression line calculated using 10 DJs at 6 different drop heights showed strong linear relationship in both phases of jump. Comparison of RFD-SF parameters obtained from isometric plantarflexion and dynamic DJ was not our primary interest, due to great differences between tasks. In the DJ task, the amount of force applied on the force plate does not depend only on the force generated from the ankle joint alone, but also from gravity and body mass. Although $r^2$ values for the DJ in the eccentric ($r^2$ = 0.87 ± 0.09) and concentric phase ($r^2$ = 0.80 ± 0.18) were smaller than for the isometric task ($r^2$ = 0.90 ± 0.06), they suggest that force-RFD relationship calculated from DJs is linear. Note that greater linearity of isometric plantarflexion task can also be attributed to a greater number of explosive contractions at each submaximal level (average number per level: 23 ± 3.4), while only 10 DJs were performed from each drop height to avoid fatigue (altogether 60 jumps). Possible influence of fatigue was equally distributed between drop heights due to randomisation.

The second aim was to investigate the relationship between slopes ($RFD\text{-}SF_{DJ\text{-}ECC}$, $RFD\text{-}SF_{DJ\text{-}CON}$ and $RFD\text{-}SF_{PF}$). Our results showed moderate relationship between $RFD\text{-}SF_{DJ\text{-}ECC}$ and $RFD\text{-}SF_{PF}$ and small associations between $RFD\text{-}SF_{DJ\text{-}CON}$ and $RFD\text{-}SF_{PF}$ which confirms our second hypothesis. As previous studies reported that RFD-SF might represent a measure of neuromuscular quickness (Bellumori et al., 2011; Klass et al., 2008), associations between slopes from both tasks could have a greater interest than other parameters. Association between plantarflexion and both phases of DJ may suggest that neuromuscular quickness of ankle joint is important for both tasks. However, the correlations were smaller than expected, even though in both, the ankle plays an important role both tasks. Moreover, there are some diversities between tasks which may influence the results. In the isometric task, the participant needs to perform quick explosive isometric contractions from a relaxed state in a non-weight bearing position. Furthermore, in DJ execution conservation of energy during eccentric phase and consequently enhanced propulsive forces (stretch–shortening cycle) (Turner and Jeffreys, 2010) creates additional force generation, which is not the case in isometric plantarflexion task. Furthermore, gastrocnemius contribution to plantarflexion is limited in the isometric task because of a flexed knee position (Landin et al., 2015) which could mean that $RFD\text{-}SF_{PF}$ performance in this position predominantly results from slow-twitch soleus muscle (Edgerton et al., 1975). This factor can partly explain smaller correlations between RFD-$SF_{DJ\text{-}ECC}$/ RFD-$SF_{DJ\text{-}CON}$ and RFD-$SF_{PF}$. Nevertheless, despite this limitation, our results suggest that ankle neuromuscular quickness plays an important role in isometric and dynamic conditions.

The third aim was to evaluate the relationship between the slopes of the regression line of both tasks (RFD-$SF_{DJ\text{-}ECC}$, RFD-$SF_{DJ\text{-}CON}$ and RFD-$SF_{PF}$) and $DJ_H$. Moderate positive relationships were observed between RFD-$SF_{DJ\text{-}ECC}$ and $DJ_H$ for jumps from 10 cm ($r = 0.459$, $p < 0.001$) and 15 cm ($r = 0.423$, $p < 0.01$), while they were weak for jumps from 20 cm ($r = 0.298$, $p < 0.05$). No significant associations were calculated between RFD-$SF_{DJ\text{-}CON}$ and $DJ_H$. The only positive weak correlation between RFD-$SF_{PF}$ was seen in $DJ_H$ from 10 cm ($r = 0.292$, $p < 0.05$) (Fig. 4). Based on these results we can partly confirm our third hypothesis. Participants with a higher RFD-$SF_{DJ\text{-}ECC}$ (10 cm, 15 cm, 20, cm) and RFD-$SF_{PF}$ (10 cm) have reached higher $DJ_H$ from the mentioned drop heights. This association is the most pronounced between RFD-$SF_{DJ\text{-}ECC}$ and $DJ_H$ from 10 cm and 15 cm (Fig. 4). It is known that force applied on the force plate increases together with an increase of drop height irrespective of training experience, age or gender (McKay et al., 2005; Seegmiller and McCaw, 2003; Walsh et al., 2004). However, participants that are able to tolerate high forces in the early phase of ground contact (eccentric phase of jump) will consequently have a greater slope in RFD-$SF_{DJ\text{-}ECC}$. This can be supported with previous studies which indicated that pre-programmed muscle activity and joint stiffness (eccentric phase) have significant contribution to the performance in DJ (Horita et al., 2002) which explains the positive relationship between RFD-$SF_{DJ\text{-}ECC}$ and $DJ_H$. Participants that were not able to tolerate overloads had smaller RFD-$SF_{DJ\text{-}ECC}$ and consequently lower $DJ_H$, as it was shown that prolonged duration of the eccentric phase results in a decrease in GRF (Leukel et al., 2008). Regarding our participants, it seems that lower drop heights (10 cm and 15 cm) were optimal (greatest correlation) for DJ performance. In line with that, as drop height increased smaller correlations between RFD-$SF_{DJ\text{-}ECC}$ and $DJ_H$ results were obtained. Namely, with progression in starting drop height ankle stiffness becomes more important since ankle force generation is not possible without it. Thus, this may explain the reduction of associations with the progression of starting drop height.

Finally, as a limitation of this study, RFD-$SF_{PF}$ measurement in the isometric task was performed unilaterally, while DJ is a bilateral task. However, we kept consistency with other isometric RFD-SF studies (Bellumori et al., 2013, 2011; Djordjevic and Uygur, 2017; Mathern et al., 2019), while DJ performed unilaterally would have questionable explosive execution. Another limitation is the measurement position in the isometric task (seated), in which the contribution of gastrocnemius as a fast twitch muscle is limited and ankle plantar flexion force is predominantly produced by the soleus muscle reach with slow twitch fibres. Furthermore, the average age of our participants was 15.1 ± 1.0 years which may influence on drop jump performance since maturation influences on jump height, especially in males (Quatman et al., 2006). However, we concluded that young agility athletes from our sample can perform acceptable DJs (short contact time, without heel strike, parabolic shape of GRF:time curve) from drop heights up to 35 cm. Future studies should elucidate the influence of measurement, i.e. joint, position on ankle plantarflexion RFD-SF, and the association between RFD-$SF_{DJ}$ and RFD-SF of knee extensors that are along with ankle plantar flexors dominant muscles in DJ, especially during the take-off phase.

In conclusion, the present study could provide novel information regarding neuromuscular quickness related to activity with high demand for a great RFD. Although multi-joint tasks such as DJs from different drop heights are often used for evaluating lower-body ballistic performance, this study is the first that introduces and verifies the rate of force development scaling factor (RFD-$SF_{DJ}$) in a dynamic condition. The proposed protocol resulted in acceptable linearity of the regression line in both phases of the DJ, regardless of the smaller number of repetitions of the progressive DJs. Our findings confirm that ankle neuromuscular quickness as represented by RFD-$SF_{PF}$/ RFD-$SF_{DJ}$ poses an important ability both in single-joint isometric plantarflexion and multi-joint DJ tasks. However, greater associations with $DJ_H$ were seen only with RFD-$SF_{DJ\text{-}ECC}$ because its performance and early phase force development is influenced by ankle stiffness, which is not the case in RFD-$SF_{DJ\text{-}CON}$ and RFD-$SF_{PF}$. Furthermore, RFD-$SF_{DJ}$ may have greater practical application than RFD-SF assessed under the isometric conditions. RFD-$SF_{DJ}$ is a single value obtained from multiple DJs which allows simple between-subjects comparison and represents a useful variable for monitoring different training adaptations (i.e. plyometrics, strength training) and their influence on neuromuscular quickness. This verification of RFD-$SF_{DJ}$ opens opportunities for further research regarding to its practical application.

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