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Neuromechanical control in submaximal drop jumps: The effects of volitional effort demands and drop height magnitude on soleus muscle activation

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Purpose: The purpose of this study was to investigate soleus muscle activation during different phases of drop jump performed at submaximal levels of volitional effort and drop height magnitude. *Methods*: Fifteen professional volleyball players with minimum of eight years of experience in jumping activities participated in the study. Experimental protocol involved executing submaximal drop jumps at three levels of volitional effort (i.e., 65, 80 and 95% of the maximal height of jump). All submaximal drop jumps were done from three drop heights (20, 40 and 60 cm). The soleus muscle activation was monitored during four jump phases: pre-activation phase before touchdown, early contact phase upon touchdown, early and late push-off phase. *Results*: The results indicate that volitional effort level did not change the muscle activation during pre activation and early contact phase, but only in early and late push-off phase ($p \leq 0.05$). Conversely, it was observed that muscle activation during all phases of drop jump was adapted to the increased intensity of the external load caused by increasing of drop height magnitude ($p \leq 0.01$). *Conclusions*: The findings of the present study suggested that soleus muscle activation has selective responses to internal load (i.e., volitional effort level) and external load (i.e., drop height magnitude) intensities when drop jump is executing with submaximal effort

Key words: *electromyography, stretch-shortening cycle, feedback control, pre activation, feedforward control, ankle biomechanics*

1. Introduction

Movement control analysis that incorporates stretch-shortening cycle muscle action is a complex topic because it includes feedforward and feedback mechanisms. From that aspect, drop jump (DJ) is very suitable motor task for examining the role of predictive and reactive control in the execution of movement [19]. Namely, for the leg extensor muscles, DJ can be divided into three phases: 1) the flight phase, i.e., preparation phase before foot contact with the ground, 2) the amortization phase i.e., early contact phase, when muscle-tendon complex is lengthened, and 3) the push-off phase followed by muscle-tendon shortening [7]. Accordingly, feedforward control affects the occurrence of muscle activation which takes place in phase of preparation for contact with the ground (also called the pre-activation) as well as the occurrence of a part of the muscle activation which occurs upon contact with the ground [25]. Further, it is assumed that most of the muscle activation which occurs during foot contact with the ground is the consequence of the feedback activity (i.e., reflexes of short, medium and long latency responses) but also depends on the interaction between the feedforward and feedback activity [19].

The previous studies have shown that the amount of pre-activation depends on the external load, i.e., level of the required motor output [4], and thus possibly explaining the increased amount of pre-activation with the increase of drop height when executing a DJ [12],

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[15]. Apart from pre-activation, it has been shown that the intensity of the primary reflex response during early contact phase increases with the drop height increase from 20 to 60 cm, while a further increase of the drop height reduces it [8]. Also, muscle activation occurring during the push-off phase ensures adequate jump performance in some DJ conditions when there is no opportunity for appearance of pre-activation (e.g., no possibility to predict the moment of foot contact with the ground) [10] or when it is not possible to activate the primary reflex responses (e.g., drop from extremely great heights) [8]. Although the drop height could variously affect the muscular activity responses during different phases of DJ execution, there are no studies which explicitly explored this important issue in submaximal drop jumps.

Most of the research dealing with the muscle activation in DJ has focused on maximal internal load, i.e., maximum level of volitional effort (hereinafter: "maximal DJ"), with instructions such as: "jump as high as possible" and/or "jump as quickly as possible" [4], [12], [14], [15], [20]. However, everyday training and competition activities often require that this movement is executed at levels that are less than the maximum, i.e., submaximal levels (hereinafter: "submaximal DJ"). This implies that the submaximal DJs are often executed during training periods in order: (i) to optimize training process in order to prevent fatigue or for rehabilitation purposes (e.g., jumping over obstacles at submaximal height), or (ii) to maximize performance of the primary task which does not require maximal height (e.g., basketball shooting, setting in volleyball). In the current literature, there are researches that describe the modulation of neuromuscular and biomechanical variables to progressively increasing submaximal volitional effort invested in vertical jumps only (squat and countermovement jumps) [9], [16], [18], [23], while there are no similar researches about DJ. However, there are important differences related to the vertical jump technique as opposed to the DJ technique, and one of the main characteristics is the existence of the pre-activation phase that influences subsequent muscle stiffness regulation and its contribution to the performance in DJ [4]. Therefore, it would be important to examine the effects of submaximal DJ tasks on muscle activation during preparation and contact phases.

Taking the importance of mentioned unresolved issues into account, the purpose of this study was to investigate soleus muscle activation during different phases of DJ performed at submaximal levels of volitional effort and different drop heights magnitudes. Therefore, we hypothesized that the soleus muscle activation during various jump phases of submaximal DJ is dependent on both volitional effort demands and drop height magnitude.

It is important to note that researchers in experimental settings often resort to monitoring the soleus muscle activation due to substantial role of plantar flexors during jumping at submaximal levels [10], [17] and its physiological advantages compared to other muscles (soleus muscle has three times as many muscle spindles and shows more consistent short latency reflex responses compared with a gastrocnemius medialis muscle) [6], [24]. Further, monitoring additional dynamic and kinematic variables could provide more detailed insight about jumping pattern and mechanisms that correspond to soleus muscle activation.

2. Materials and methods

2.1. Subjects

Fifteen professional volleyball players, the average age of 21.1 (±1.6) years, height 190.4 (±8.2) cm, body mass 81.5 (±6.9) kg and maximum countermovement jump height of 0.45 (±0.04) m participated in the present study. They had a minimum of eight years of experience in active volleyball playing. Subjects did not have any injuries or surgeries on the locomotor system in the last 6 to 12 months that influenced their regular training activities. The entire experiment was carried out with the approval of the Ethics Committee of the Faculty of Sport and Physical Education, University of Belgrade and all subjects signed an informed consent form according to the Helsinki Declaration.

2.2. Experimental design

An experimental design was set to investigate the effects of the three levels of volitional effort (65, 80 and 95% of maximal height of jump), the three levels of drop height (20, 40 and 60 cm) and the four phases of the DJ execution (pre-activation phase, early contact phase upon touchdown, early and late push-off phase) on the soleus muscle activation. The volitional efforts over the 65% were taken for the jump task because the subjects were not able to perform DJ correctly when the instruction was performing DJ at the heights below that. The experimental protocol consisted of two testing sessions, out of which the first session was used for anthropometric measurements and familiarization with the motor tasks, while the second session (after 48 hours) was the main testing during which the acquisition of electromyography (EMG), kinematic and dynamic variables were performed. Note that the data obtained from dynamic and kinematic variables recorded during execution of submaximal DJ tasks should provide more detailed insight about jumping pattern and mechanisms that correspond to soleus muscle activation.

2.3. Data collection

EMG, kinematic and dynamic data were collected simultaneously via internal synchronization. The telemetry EMG device (Myomonitor IV, DelSys Inc. Boston, MA, USA) with individual differential silver chloride electrodes (DE – 2.1) (a contact sensor of 2 silver plates of 10 mm length and of 1 mm width, i.e., a contact surface of 10 mm^2) was used for EMG analysis and the signal sampling frequency was 2000 Hz. After preparing the skin, surface electrodes were placed on the soleus muscle surface following the procedure in accordance with the recommendations of SENIAM (surface electromyography for the non-invasive assessment of muscles). Force plate (BP400600, AMTI, MA, USA) was used to record the ground reaction force at signal sampling frequency of 2000 Hz. Kinematics of movement was monitored by infrared cameras (Qualysis MCU 240 ProReflex, Qualysis, Sweden) which recorded the positions of retro-reflecting 19 mm diameter markers on sampling frequency of 240 Hz. In order to monitor the kinematic variables, a set of eleven retro-reflecting markers was placed on the dominant side of the subject at the following positions: the distal head of the fifth metatarsal, heel, ankle, knee joint, hip joint, shoulder joint, elbow joint, wrist, hand, sternoclavicular joint and head. Anatomical landmarks for the marker position were defined based on the Dempster's Segment Endpoint Definitions [2].

2.4. Testing procedure

The warm-up, which consisted of 10 minutes cycling, active stretching, hopping and double leg vertical jumping, was followed by setting the electrodes for EMG analysis and markers for kinematic analysis on the leg which is the subject's dominant leg for the jump execution. Subjects first implemented DJ with maximal level of effort which was followed by performing submaximal DJ.

Maximal drop jumps

The first experimental task was to implement three DJs with a maximum volitional effort separately from each of the drop heights: 20, 40 and 60 cm. Instructions for DJ movement tasks were that the subject stands at the edge of the box with arms akimbo and without moving them during the execution of the jump, then to step out with the dominant leg and slide down from the box with the straight non-dominant leg. The instructions given to the subjects when performing maximal DJ were to perform maximum volitional effort with the shortest possible contact with the ground. Each of the subjects performed a total of 9 maximal DJ (3 jumps × 3 drop heights). The pause between jumps that were executed from the same drop height was about 1 min and if drop height changed a pause was 2 min. Maximum volitional effort was determined based on the maximum jump height performed by the participant. Each subject performed three maximal height jumps for each drop height from which averaged maximal jump height was calculated.

Submaximal drop jumps

After executing maximal DJs, the second movement task was execution of submaximal DJs. Submaximal volitional efforts were determined for each particular drop height separately and represent 65, 80 and 95% of the maximum effort (100%). Jump height achieved in maximal DJ was used for calculation of target jump heights for submaximal effort levels of 65,

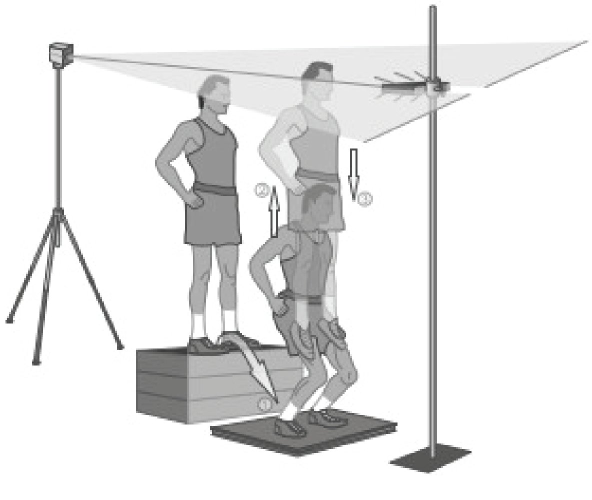

Fig. 1. Display of experimental set up and two methods for controlling the volitional effort. Using an infrared beam from the device that was located behind the subject, the experimenter controlled if the control point that was marked on the subject reached the target jump height. Based on the light signal system which was located in a box in front of him the subject had feedback information whether he jumped to the target jump height

80 and 95%. Subjects were able to control the volitional effort based on visual signal that was put in front of them and from the feedback information given by the experimenter. A visual signal in the form of box – 20 cm wide, 10 cm long and 2 cm high, open on one long side toward the subject, and with a line of horizontally placed LEDs on the opposite inner side were set at a target height to which the subject should jump (Fig. 1).

Heights of the box were calculated in the following manner: value of submaximal target height (65, 80 or 95%) was added to the height of the retro-reflective marker which was placed above the upper edge of the ear auricle aligned with the eye socket (retro-reflective marker placed at the head) with subject standing upright. The box was attached to vertically mounted meter with a sliding mechanism enabling the box to be placed at a certain height, and always on a proper horizontal plane relative to the ground. Instructions which a subject had to follow when performing submaximal DJ, were to achieve the target jump height with the shortest contact with the ground. The subject had to jump just enough to see light markings, but no higher. It is understood that the body at that point had to be completely straight in the vertical direction. In addition, there was also an external visual control of the completed task by the experimenter, including the use of the linear laser (PCL20, Bosch, Germany), which was located behind the subjects (Fig. 1). The unit spread red line beam in the same horizontal plane with light markings (i.e., level of target jump height). The accuracy of the device was ± 0.5 mm/m. Successfully performed task meant that the subject had cut the beam at the level of upper edge of the ear auricle, i.e., retro-reflecting marker placed in the plane of the eye socket (head marker), and it was controlled by the experimenter. If the subject had performed lower jump height in relation to the target jump height, the experimenter gave the instruction "*jump little higher in the next trial*", and if the subject had performed higher jump height in relation to the target jump height the experimenter gave the instruction "*jump little lower in the next trial*". Each of these 3 drop heights × 3 volitional efforts combinations was performed 7 ± 1 times in a random order, out of which the average of the five most successful jumps was used for further analysis. First, subject performed DJs from the 20 cm drop height with different levels of volitional effort (first, all jumps at 95%, then 65%, and finally 80%), then the same procedure was repeated from the 60 cm drop height, and finally, from the 40 cm. Each of the subjects performed a total of 63 ± 9 submaximal DJs. The pause between jumps that were executed from the same drop height and for the same volitional efforts was about 30 sec. In addition to the 30 sec pauses, when the volitional effort changed, the pause lasted about 1 min, and if drop height changed, the pause was 2 min [13].

2.5. Data analysis

Electromyographic data were analyzed with the aid of the custom-built LabView software designed for processing of the EMG signal (LabView, National Instruments, Austin, TX, USA). The raw EMG signal was first filtered via band-pass filter in the range of 10–750 Hz. For the analysis of muscle activity root mean square (RMS) value was determined for the four phases of a DJ and each phase lasted 60 ms: preactivation phase ($P_{(-60-0)}$), the early contact phase upon touchdown ($P_{(0-60)}$), the early push-off phase ($P_{(60-120)}$) and the late push-off phase ($P_{(120-180)}$); index "0" denotes the moment of time of the subject's contact with the ground [10]. RMS values were normalized relative to the maximum values of RMS achieved when executing DJ from the highest drop height (60 cm). The value selected as the delay between EMG signal and ground reaction force output during any trial was 60 ms.

The values of net impulse (I_{net}) were determined from the force plate data. Jump height was measured based on the height reached by the centre of mass at the apex of the jump relative to the height of the centre of mass in upright standing. Body parameters for the center of mass (CoM) position were defined according to Dempster's model. Calculation of CoM kinematics was based on anthropometric measures of subjects and the time history of the retro-reflecting markers position [2]. Also, the values of center of mass velocity at touchdown (CoM_{Vtd}), center of mass height at touchdown (CoM_{Htd}), center of mass height at deepest point (CoM_{Hdp}), center of mass height at take-off (CoM_{Hto}), ankle angle at touchdown (θ_{td}), ankle angle at deepest point (θ_{dp}) and ankle angle at take-off (θ_{to}) were measured from the kinematic data. All results of CoM height were expressed as a percentage of the subjects CoM height at upright standing.

2.6. Statistical analysis

Descriptive statistics were calculated for all experimental data as mean and standard deviation (SD). Note that applied Shapiro–Wilk test confirmed the normality of the distribution ($p > 0.05$) for dependent variables in all experimental conditions. To explore absolute and relative reliability intraclass correlation coefficients (ICCs: model 3,1) were used to determine between-subject reliability [21], whereas within-subject variation was determined by calculating coefficient of variation (CV) [3]. Also, ninety-five percent confidence intervals (95% CI) were determined for ICC and CV.

In order to determine the effect of the drop height (20, 40, 60 cm), the volitional effort (65, 80, 95%) and the *jump phases* ($P_{(-60–0)}$, $P_{(0–60)}$, $P_{(60–120)}$ and $P_{(120–180)}$) on soleus muscle activation, a three-way ANOVA with repeated measures was used (3 drop heights × 3 volitional efforts × 4 jump phases). To determine the effect of the drop height and the volitional effort on the, I_{net}, CoM_{Htd}, CoM_{Hdp}, CoM_{Hto}, CoM_{Vtd} and θ_{td}, θ_{to}, θ_{dp}, the results were analyzed by two-way analysis of variance with repeated measures ANOVA (3 drop heights × 3 volitional efforts). If the assumption of sphericity was not met, the Greenhouse–Geisser correction for *df* and *F* values was used. After the ANOVA statistical analysis determined significant influence of any factor or significant effect of factor interaction, *post-hoc* analysis were carried out using the *t*-test method for dependent samples with a Bonferroni–Holm correction. For post-hoc tests for the assessment of effect size Cohen's *d* (d) was used where the effect of 0.2 < is trivial, 0.2–0.5 small, 0.8 – moderate, and > 0.8 – large [21]. Values of $p \leq 0.05$ were selected to determine the level of statistical significance. All statistical tests were conducted using SPSS 17.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Electromyography

Figure 2 shows values of ground reaction force and EMG of soleus muscle for one subject, during execution of DJ at different volitional efforts (65, 80 and 95%),

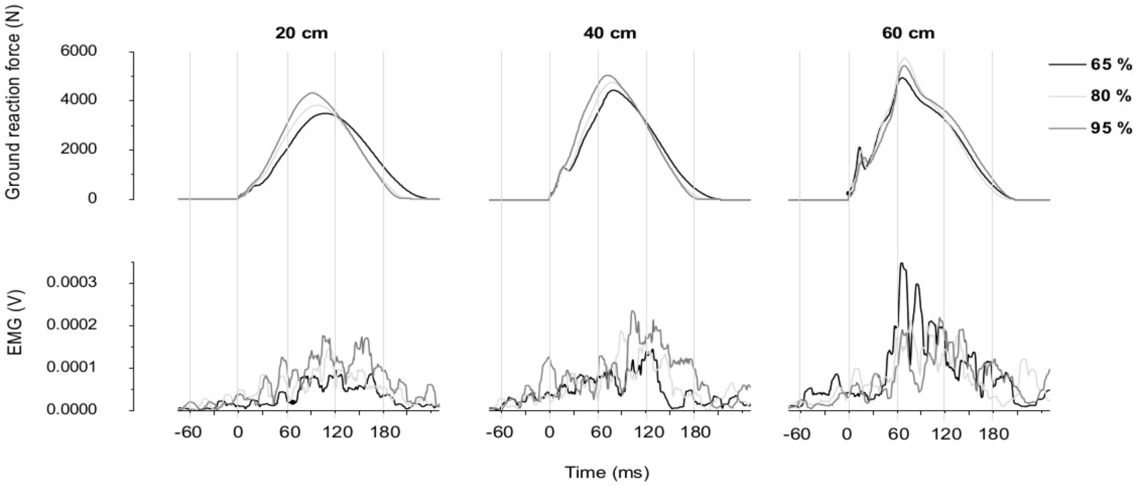

Fig. 2. The results of the ground reaction force (upper panel) and soleus muscle activity (lower panel) for one subject in DJ performed at different volitional efforts (65, 80 and 95%) separately for each drop height (20, 40 and 60 cm). The vertical lines divide phases of DJ execution from the moment of foot contact with the ground which is labeled with zero on the diagram (0)

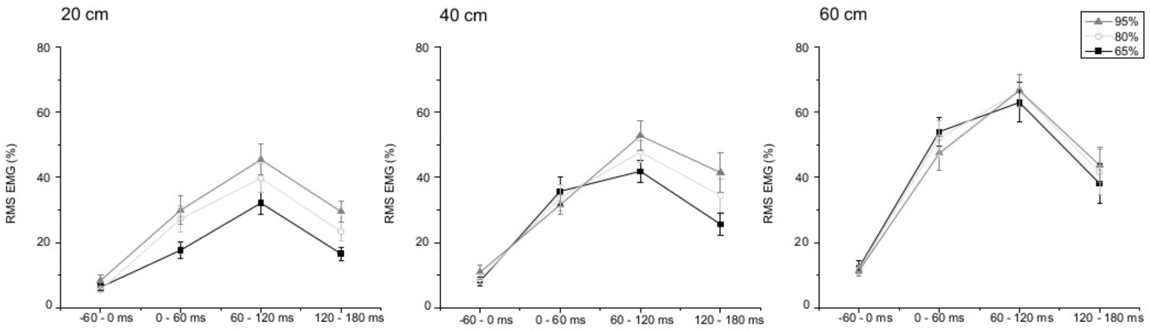

Fig. 3. The RMS results of soleus muscle (mean ± SD) during different phases of DJ execution ($P_{(-60–0)}$, $P_{(0–60)}$, $P_{(60–120)}$ and $P_{(120–180)}$) and different volitional efforts (65, 80 and 95%) separately for each drop height (20, 40 and 60 cm). RMS values are expressed as a percentage of the maximum RMS value obtained when executing a maximal DJ from the drop height of 60 cm

separately for each drop height (20, 40 and 60 cm). It may be noted that the increase of the volitional effort increases soleus muscle activation only in the third and fourth phases of a DJ ($P_{(60–120)}$ and $P_{(120–180)}$). Pre-activation and first muscle response in activation upon contact with the ground ($P_{(–60–0)}$ and $P_{(0–60)}$) remained unchanged. This change is particularly obvious at drop heights of 20 to 40 cm, but not at the drop height of 60 cm. On the other hand, increasing the drop height increased the intensity of the muscle activation in all phases of the DJ ($P_{(–60–0)}$, $P_{(0–60)}$, $P_{(60–120)}$ and $P_{(120–180)}$).

Mean values (± SD) for the RMS of soleus muscle during the different phases of execution of a DJ ($P_{(–60–0)}$, $P_{(0–60)}$, $P_{(60–120)}$ and $P_{(120–180)}$) and different volitional efforts (65, 80 and 95%) separately for each drop height (20, 40 and 60 cm) are shown in Fig. 3.

The results of three-way ANOVA yielded significant effects of double interaction for drop height × jump phase ($F_{(2.799,\ 39.184)} = 7.19$; $p \le 0.001$), for the volitional effort × jump phase ($F_{(6,\ 84)} = 8.15$; $p \le 0.001$), as well as for the drop height × volitional effort ($F_{(4,\ 56)} = 5.59$; $p \le 0.001$) on RMS, with no triple interaction effect ($p \ge 0.05$). The main finding from the post-hoc analysis demonstrated that the muscle activation significantly increases in the later phases ($P_{(60–120)}$ and $P_{(120–180)}$) of the jump execution with the increase in the volitional effort ($65 < 80 < 95\%$; $p \le 0.05$; $d = 0.96–2.30$), while there was no evidence of a change in the early phases of jump ($P_{(–60–0)}$ and $P_{(0–60)}$). In addition, muscle activation in all phases of the DJ execution significantly increased with an increase in the drop height ($20 < 40 < 60$ cm; $p \le 0.01$; $d = 1.30–6.02$). Finally, overall muscle activation significantly increased with increase of the volitional effort only when DJ executed from both the small (20 cm) ($65 < 80 < 95\%$; $p \le 0.05$; $d = 1.06–2.83$) and medium (40 cm) ($65 < 80 < 95\%$; $p \le 0.05$; $d = 0.63–1.41$) drop heights, but not from larger (60 cm) drop height.

3.2. Dynamics and kinematics

It can be noted that at the target volitional effort of 65% of subjects realized somewhat lower heights (58.8–61.9%), which is not the case with the target volitional efforts of 80% and 95% (77.5–82.0% and 95.4–96.8%, respectively). Our opinion is that this difference does not affect the purpose of the given motor task because the purpose was not performance accuracy, but defining landmarks for volitional effort level which subjects should perform. In addition, the reliability analysis for the five successful jumps for each of 3 drop heights × 3 volitional efforts combinations revealed satisfactory between-subject and within-subject reliability Specifically, for the volitional effort of 65% CV was between 7.6–10.0% (95% CI 4.8–13.8%) and ICC was 0.94–0.95 (95% CI 0.84–0.99). For the volitional effort of 80% CV was between 4.8–6.8% (95% CI 3.0–9.2%) and ICC was 0.93–0.98 (95% CI 0.84–0.99). For the volitional effort of 95% CV was between 4.0–7.0% (95% CI 2.5–9.5%) and ICC was 0.94–0.98 (95% CI 0.87–0.99). In addition, systematic bias was not detected among jumps at the same volitional effort ($p \ge 0.05$).

Table 1. Statistics results for dynamics and kinematics among different volitional effort and drop height conditions

	Drop height	Volitional effort	Drop height × Volitional effort
I_{net}	$p \le 0.001$, $F_{(2,28)} = 1083.56$	$p \le 0.001$, $F_{(2,28)} = 276.94$	$p \le 0.05$, $F_{(2.456,34.378)} = 4.538$
CoM_{Htd}	$p \le 0.001$, $F_{(2,28)} = 178.00$	$p \le 0.001$, $F_{(2,28)} = 21.43$	$p \le 0.001$, $F_{(4,56)} = 5.78$
CoM_{Hdp}	$p \le 0.001$, $F_{(1.338,18.728)} = 17.17$	$p \le 0.001$, $F_{(1.243,17.408)} = 31.36$	$p \le 0.001$, $F_{(2.723,36.695)} = 7.39$
CoM_{Hto}	$p \le 0.05$, $F_{(2,28)} = 0.41$	$p \le 0.05$, $F_{(2,28)} = 0.21$	$p \le 0.05$, $F_{(4,56)} = 0.50$
CoM_{Vtd}	$p \le 0.001$, $F_{(2,28)} = 866.00$	$p \le 0.001$, $F_{(2,28)} = 28.0$	$p \le 0.001$, $F_{(4,56)} = 9.03$
θ_{td}	$p \le 0.001$, $F_{(1.121,15.692)} = 53.18$	$p \le 0.001$, $F_{(2,28)} = 40.84$	$p \le 0.05$, $F_{(1.711,23.951)} = 2.31$
θ_{dp}	$p \le 0.001$, $F_{(1.329,18.600)} = 61.94$	$p \le 0.001$, $F_{(2,28)} = 28.44$	$p \le 0.001$, $F_{(4,56)} = 6.52$
θ_{to}	$p \le 0.05$, $F_{(2,28)} = 0.41$	$p \le 0.05$, $F_{(2,28)} = 0.21$	$p \le 0.05$, $F_{(4,56)} = 0.84$

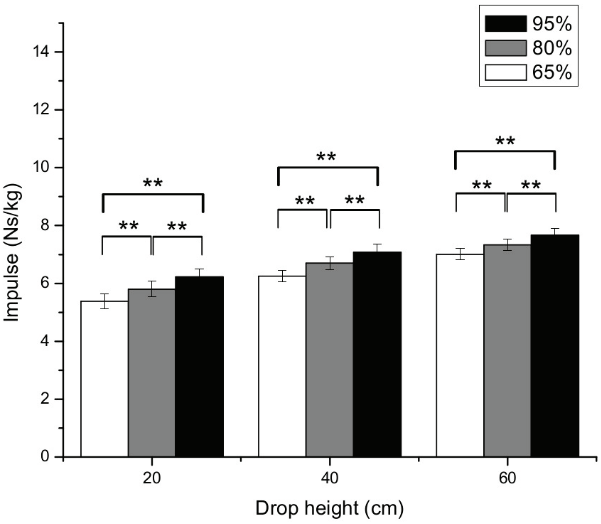

Fig. 4. Mean ± SD of net impulse in DJ from different drop heights (20, 40 and 60 cm) and at different volitional effort levels (65, 80 and 95%). Statistical differences between the different volitional effort levels are marked with asterisks (* for $p \leq 0.05$ and ** for $p \leq 0.01$; $d = 1.53–3.37$). Furthermore, net impulse significantly increased along with the increase of the drop height level ($20 < 40 < 60$; $p \leq 0.01$; $d = 2.36–7.14$)

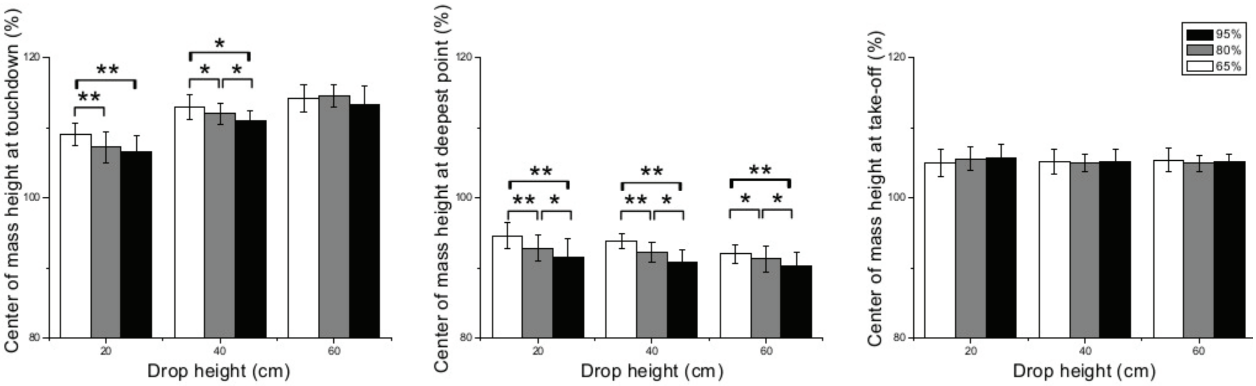

Fig. 5. Mean ± SD of center of mass height at touchdown, center of mass height at deepest point and center of mass height at take-off in DJ from different drop heights (20, 40 and 60 cm) and at different volitional effort levels (65, 80 and 95%). All results of CoM height are expressed as a percentage of the subjects CoM height at upright standing. Statistical differences between the different volitional effort levels are marked with asterisks (* for $p \leq 0.05$ and ** for $p \leq 0.01$; $d = 0.62–1.27$ ($\mathrm{CoM}_{\mathrm{Htd}}$) and $d = 0.44–2.05$ ($\mathrm{CoM}_{\mathrm{Hdp}}$)). Furthermore, there was significant increased of $\mathrm{CoM}_{\mathrm{Htd}}$ with increase of the drop height level ($20 < 40 < 60$; $p \leq 0.05$; $d = 0.66–3.76$). Also, $\mathrm{CoM}_{\mathrm{Hdp}}$ decreased with increase drop height when subjects executing DJ with 65% ($20 > 40 > 60$; $p \leq 0.05$; $d = 0.47–1.57$) and 80% ($20 = 40 > 60$; $p \leq 0.001$; $d = 0.62–0.84$) of the volitional effort, but it did not change depends on drop height when executing DJ with 95% of volitional effort ($p \geq 0.05$)

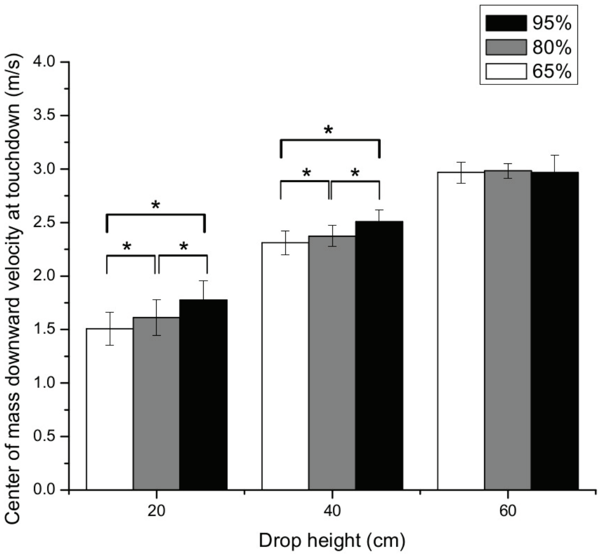

Fig. 6. Mean ± SD of center of mass velocity at touchdown in DJ from different drop heights (20, 40 and 60 cm) and at different volitional effort levels (65, 80 and 95%). Statistical differences between the different volitional effort levels are marked with asterisks (* for $p \leq 0.05$ and ** for $p \leq 0.01$; $d = 0.60–1.79$). Furthermore, center of mass velocity at touchdown was significant increased with increase of the drop height level ($20 < 40 < 60$; $p \leq 0.001$; $d = 3.27–11.28$)

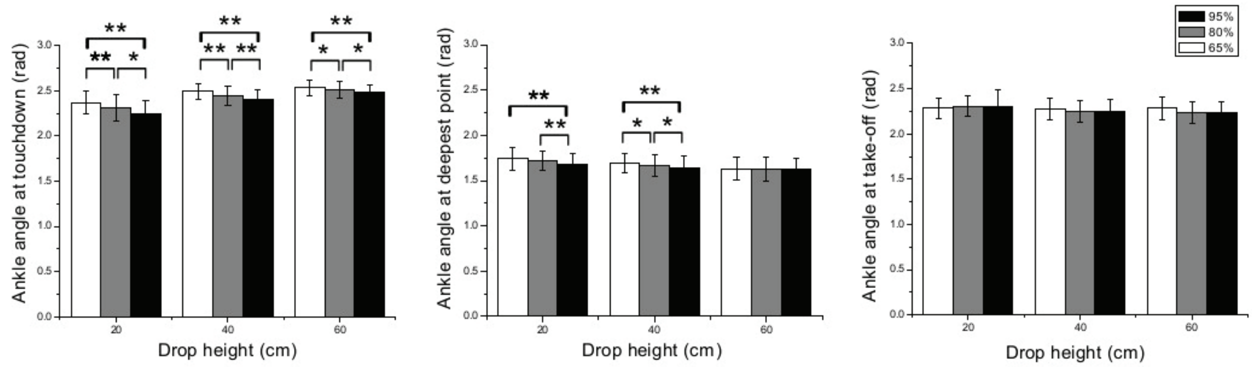

Fig. 7. Mean ± SD of ankle angle at touchdown, ankle angle at deepest point and ankle angle at take-off in DJ from different drop heights (20, 40 and 60 cm) and at different volitional effort levels (65, 80 and 95%). Statistical differences between the different volitional effort levels are marked with asterisks (* for $p \leq 0.05$ and ** for $p \leq 0.01$; $d = 0.35$–0.81 (θ_{td}) and $d = 0.17$–0.49 (θ_{dp})). Furthermore, for the θ_{td} there was a significant difference between each level of the drop height ($20 < 40 < 60$; $p \leq 0.001$; $d = 0.60$–1.68). Also, post-hoc analysis showed that θdp decreased with increase of the drop height (20 > 40 > 60 cm; $p \leq 0.001$; $d = 0.17$–0.90)

Obtained results from dynamic and kinematic variables recorded during execution of submaximal DJ tasks provided more detailed information about jumping pattern and mechanisms that correspond to soleus muscle activation. The results of two-way ANOVA are presented in Table 1 and details of obtained post-hoc analyses are reported in Figs. 4–7.

Results for I_{net} showed that there were significant differences among levels for both, drop height and volitional effort (Table 1, Fig. 4). The main results for CoM position revealed that both CoM_{Htd} and CoM_{Hdp} decreased along with the increase of the volitional effort, but not for CoM_{Hto} (Table 1, Fig. 5). Especially for CoM_{Htd}, there is no change depends on volitional effort when executing DJ from large (60 cm) drop height, but only for small (20 cm) and medium (40 cm) drop height (Fig. 5), which corresponds to results obtained for CoM_{Vtd} (Fig. 6). It could be noted that the results for the ankle angle coincide with some results of CoM position, where both θ_{td} and θ_{dp} decreased with increase of the volitional effort, but not for θ_{to} (Table 1, Fig. 7).

4. Discussion

The purpose of this study was to investigate the soleus muscle activation in DJ at different submaximal volitional effort levels (65, 80 and 95% of maximum effort) executed from different drop heights (20, 40 and 60 cm). The activation of soleus muscle was monitored during four phases of the DJ execution (pre-activation phase, early contact phase, early and late push-off phase), followed by recording of complementary dynamic and kinematic variables for better understanding of jumping pattern and mechanisms that correspond to soleus muscle activation. It was assumed that different levels of volitional effort and drop height have an effect on changing in soleus muscle activation during various phases of submaximal DJ execution. Bearing in mind the observation that the above-mentioned factors confirmed certain influence on soleus muscle activation, our hypothesis was confirmed. The following text is focused on the interpretation of these main findings.

The results of this study indicate that drop height (i.e., external load) significantly affected the intensity of muscle activation in the phase prior to foot contact with the ground, as opposed to the volitional effort that did not have influence on adjustment of the pre-activation intensity. In previous studies the pre-activation is marked as a phenomenon that is a very important for the preparation of the muscle-tendon complex for jump execution [4], [5]. As part of the pre-programmed or feedforward control, the pre-activation provides a certain degree of stiffness of the muscles [20]. Based on the fact that the subjects in our study were asked to perform jumps at different volitional efforts which have been pre-marked and known in advance, the result which shows that there was no changing in pre-activation regarding to internal load intensity (i.e., jump height) was partly unexpected. On the other hand, subjects adapted pre-activation to change in drop height, which emphasizes the role of pre-programmed control in adapting to the external load intensity (i.e., drop height). These findings are consistent with previous research which presented a linear relationship between the pre-activation of the plantar flexor muscles and drop heights [12], [15]. It is noteworthy that the I_{net} was strongly affected by the volitional effort and drop height. Based on that, it could be argued that different volitional effort levels and drop height magnitudes could caused different mechanical condition for DJ execution where I_{net} could represent valid and sensitive variable to support testing the hypothesis of this study.

An important result of this study is that the changes in volitional effort (i.e., internal load) affect the adjustment of the soleus muscle activation in later phases of DJ execution ($P_{(60–120)}$ and $P_{(120–180)}$). The absence of increase in muscle activation with increase in volitional effort during initial phase of contact with the ground is supported with previous finding that the rapid adjustment in musculoskeletal stiffness is the result of passive mechanisms and that neural feedback activity is not necessary for this change [22]. In particular, for the results of this study, it is noteworthy that even in the phases of the push-off from the ground, an increased amount of muscle activation with increase in drop heights was observed (60 to 180 ms from the beginning of contact). This has not been observed in previous research where the change in drop height in maximal DJ primarily affected the change of pre-activation and muscle activation during the early contact phase, while there was no change in the muscle activation during push-off phase [15]. It is possible that specific-movement task used in our study, that is, execution of DJ at submaximal height, influenced the observed phenomena that the increase of the drop height increases the intensity of muscle activation in push-off phase, not just at the pre-activation and early contact phase.

The results of this study indicate that the volitional effort affected the changes in overall soleus muscle activation during the DJ from drop height of 20 to 40 cm, but not at the drop height of 60 cm. Similarly, in some of the earlier research it is shown that subjects were not able to adjust muscle activation during submaximal DJ from larger drop heights due to the involvement of inhibitory mechanisms influencing the reduction of stretch reflex, which has been shown to have a significant effect on power production during the push-off phase [5], [14]. Accordingly, it may be considered that during the DJ from 60 cm it is above all important to produce adequate activation of the muscle to neutralize a large amount of kinetic energy that is gained in the flight phase. Note that passive muscle properties could gain muscle force and energy dissipation because of increased stretch velocities of muscle fibers caused by the augmented drop height. Similar trend of the results of the body position at touchdown supported this statement. Lowering the CoM at touchdown seems to be beneficial effect for the increasing jump height, i.e., volitional effort. It could be noticed that during DJ from 60 cm, the subjects were not able to finely adjust the $\mathrm{CoM}_{\mathrm{Htd}}$, for the purpose of creating the adequate initial position for increasing of volitional effort, as it was possible from the drop heights of 20 and 40 cm. Changes in CoM position that represents kinematic of the whole system, and ankle angle as its component, could give some explanation about the increasing in muscle activation with augmented volitional effort. CoM and ankle angle were lower at touchdown and at deepest point during contact phase during DJ at larger volitional efforts. Deeper position of the system could changed the transfer between muscle forces and acceleration of CoM in a manner that it was necessary to increase muscle activation to provide enhancement of jump height. The aforementioned results obtained could be explained by the fact that when analyzing soleus muscle activation it was not possible to identify all factors that influence the jump performance. Therefore, it could be assumed that some of the other components of the muscle (e.g., viscous or elastic component) have a role in the production of muscle power in the execution of the high intensity DJ [11]. Also, one important observation was that lowering CoM at touchdown when subjects trying to jump higher caused an increase in the duration of the flight phase before touchdown, which further increased the CoM downward velocity at touchdown. This could partially explain the unchanged muscle activation during the initial phase of ground contact when subjects tried to jump higher, supported with results of recent research, which emphasized the importance of muscle properties in control of jumping where at the same activation muscles will produce force depending on the speed of lengthening [1].

It is important to note that this research is one of the first studies dealing with the neuromechanical control in submaximal DJ but also it has several methodological limitations that may additionally explain the results and set some directions for future research. First, subjects who participated in this experiment were professional volleyball players who have extensive experience in performing DJ. Accordingly, the results of this study obviously possess appropriate internal validity. However, they should not be generalized onto the wider population due to of lower external validity. For example, a result in this study which shows that the subjects were able to finely control the muscle activation at the drop height of 40 cm regarding the controlling of volitional effort, may not apply to a population that has no experience in performing these jumps. Second, in this study we used the results of activation of one muscle – soleus muscle. In addition to explanations given in the introduction some researches claim that soleus muscle has three times as many muscle spindles [6] and shows more consistent short latency reflex responses compared with a gastrocnemius medialis muscle [24] that further justifies the using soleus muscle in this experimental setting. However, some of the other muscles that are involved in executing DJ movement may also be important for jump performance. For this reason, we have also measured activation of other leg muscles in addition to the soleus muscle activation, but due to a large number of the results we did not include them into this article. Thus, in future studies it is important to examine the role of other muscles to control submaximal DJ. The last limitation refers to the determination of DJ phases for EMG monitoring. Four phases were determined in advance based on the moment of foot contact with the ground (–60–0, 0–60, 60–120 and 120–180 ms), but not on the kinematics of center of mass (e.g., countermovement and take-off phases). It is important to note that the neuromuscular response of soleus muscle depends very much of the moment of the foot contact with the ground [10]. It seems that investigating the neuromuscular response of soleus muscle in relation to moment of foot contact was more important than measuring soleus muscle activation according to the center of mass kinematics. Since this study revealed that submaximal DJ has some differences in muscle activation during different phases of DJ compared to maximal DJ, it would be interesting to explore how these differences manifest after certain training interventions.

5. Conclusions

The findings of the present study have shown that soleus muscle activity have their specificities when executing DJ with submaximal effort. Hence, a few conclusions could be made. First, increasing of the volitional effort in submaximal DJ increases the soleus muscle activation in the late push-off phase (i.e., 60 to 180 ms from the beginning of contact with the ground). This indicates that the muscle activity response during push-off phase takes the most important part in the volitional effort control. Second, comparing to previous studies, changing the drop height during submaximal DJ required muscle activation adjustment during all phases of movement execution, while in performing maximal DJ muscle activation only in the pre-activation and early contact phase is changed. Third, in performing DJ from higher drop heights (i.e., 60 cm) it seems that soleus is not able to adjust the muscle activation to different volitional efforts as is in the case with lower drop heights (i.e., 20 and 40 cm). It follows that dosing of volitional effort in DJ which is performed from higher drop heights does not have the same pattern of soleus neuromuscular activity like dosing of volitional effort in DJ which is performed from lower heights. In addition to this statement, it is important to mention that all kinematics and dynamics variables were not adjusted to different volitional efforts during DJ from 60 cm, as was the case for DJ from 20 and 40 cm, that further supports specifics of performing submaximal DJ from higher drop heights compare to lower drop heights.

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Conflict of interest statement

The authors declare that they have no conflict of interest.

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