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Effects of fatigue and surface instability on neuromuscular performance during jumping

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It has previously been shown that fatigue and unstable surfaces affect jump performance. However, the combination thereof is unresolved. Thus, the purpose of this study was to examine the effects of fatigue and surface instability on jump performance and leg muscle activity. Twenty elite volleyball players (18 ± 2 years) performed repetitive vertical double-leg box jumps until failure. Before and after a fatigue protocol, jump performance (i.e., jump height) and electromyographic activity of selected lower limb muscles were recorded during drop jumps (DJs) and countermovement jumps (CMJs) on a force plate on stable and unstable surfaces (i.e., balance pad on top of force plate). Jump performance (3–7%; $P < 0.05$; $1.14 \leq d \leq 2.82$), and muscle activity (2–27%; $P < 0.05$; $0.59 \leq d \leq 3.13$) were lower following fatigue during DJs and CMJs, and on unstable compared with stable surfaces during DJs only (jump performance: 8%; $P < 0.01$; $d = 1.90$; muscle activity: 9–25%; $P < 0.05$; $1.08 \leq d \leq 2.54$). No statistically significant interactions of fatigue by surface condition were observed. Our findings revealed that fatigue impairs neuromuscular performance during DJs and CMJs in elite volleyball players, whereas surface instability affects neuromuscular DJ performance only. Absent fatigue × surface interactions indicate that fatigue-induced changes in jump performance are similar on stable and unstable surfaces in jump-trained athletes.

Vertical jumps are crucial components of athletic performance in a variety of sport disciplines, especially in volleyball (e.g., blocking, serving, and attacking). In general, these activities consist of muscle actions in the stretch-shortening cycle (SSC). The SSC is a natural pattern of muscle activation that stores elastic strain energy in the muscle tendon complex during the eccentric or braking phase of a preactivated muscle and partly reutilizes the previously stored energy during the subsequent concentric or push-off phase (Komi, 2002).

During training and/or competition, volleyball players have to perform a large number of SSC actions (e.g., block jumps, spike jumps, serve jumps), which result in acute skeletal muscle fatigue (Ribeiro et al., 2008; Magalhaes et al., 2011). Acute skeletal muscle fatigue (thereafter referred to as fatigue) is defined as a reversible exercise-induced reduction in muscle performance, irrespective of task completion (Bigland-Ritchie & Woods, 1984). In fact, it has previously been shown that fatigue protocols which include repetitive SSC movements lead to decrements in jump performance and neuromuscular activity (Komi, 2002). For instance, the performance of maximal continuous jumps or repetitive maximal drop jumps (DJ) resulted in a decrease in jump height during DJs and/or countermovement jumps (CMJ) (Skurvydas et al., 2000, 2002; Rodacki et al., 2001).

Of note, particularly in beach volleyball, jumping often occurs on unstable surfaces (e.g., sand) during training and competition. According to the principle of training specificity, training has to closely mimic the demands of competition (Behm & Sale, 1993), which is why artificial unstable surfaces (e.g., balance pads) are often included in specific plyometric exercise programs (Granacher et al., 2015). Previous studies examined the effects of surface instability on jump performance and lower limb muscle activities. The reported outcomes were highly task (e.g., squats, jump landings, DJs, CMJs) and/or surface specific (e.g., compliant sprung surface, balance pad). For instance, Arampatzis et al. (2004) demonstrated a higher DJ height when jumping on a compliant sprung surface compared with a stable surface. In contrast, Prieske et al. (2013) found lower jump heights when DJs were performed on a foam balance pad compared with stable condition. Moreover, when performing CMJs on the same balance pad, no performance differences were observed between unstable and stable conditions (Howard et al., 2015). Task and surface specific effects were also found for lower limb muscle activities during jumping and landing on stable as compared with unstable surfaces. For instance, Márquez et al. (2014) reported similar leg muscle activities during submaximal hoppings on unstable (i.e., gymnastic spring floor) compared with stable surface, whereas Prieske et al. (2013) observed reduced lower leg muscle activities during the performance of DJs on unstable surfaces (i.e., balance pad).

It is crucial to know how fatigue modulates measures of jump performance and muscle activity when athletes are exposed to unstable devices that are frequently used in athletic training and rehabilitation (e.g., balance pads). This information is important for the development and design of effective and safe (plyometric) training regimes in elite athletes. There is hardly any information available in the literature regarding the effects of fatigue on jump performance using unstable as compared with stable surface conditions. With regard to balance performance, Bisson et al. (2012) were able to show that fatigue produced larger performance decrements when balancing on an unstable device as compared with stable ground.

Therefore, the objectives of this study were to examine the effects of fatigue administered as repetitive vertical jumps on (a) performance variables (e.g., jump height, performance index) and (b) leg muscle activities during DJs and CMJs on unstable compared with stable surfaces. With reference to the aforementioned findings (Skurvydas et al., 2000, 2002; Rodacki et al., 2001; Komi, 2002; Prieske et al., 2013), we hypothesized that jump performance and leg muscle activities decrease with fatigue and surface instability. In addition, we expect that fatigue-related changes in jump performance and/or leg muscle activities are more pronounced under unstable compared with stable conditions.

Methods

Participants

Twenty healthy male ($n = 10$) and female ($n = 10$) volleyball players aged 16 to 23 years volunteered to participate in this study. Participants' characteristics are presented in Table 1. The elite volleyball players were recruited from volleyball clubs competing in the third ($n = 1$), second ($n = 17$), or first ($n = 2$) division of the German Volleyball Association. An *a priori* power analysis (Faul et al., 2007) with an assumed type 1 error of 0.05 and a type 2 error rate of 0.20 (80% statistical power) was conducted for measures of CMJ performance (Howard et al., 2015). The analysis revealed that 20 subjects would be sufficient for finding a statistically significant main effect for the factor fatigue (i.e., non-fatigued vs fatigued) and/or surface (i.e., stable vs unstable surface). Participants were excluded if they had any history of musculo-skeletal, neurological, or orthopedic disorder in the lower extremities within the preceding 6 months that might have affected their ability to execute the experimental protocol. Before the start of the study, participants were familiarized with the experimental protocol and potential risks. Written informed consent was obtained from the participants and their legal guardians in case they were aged < 18 years. Ethical permission was provided by the local ethical commission of the University of Potsdam (submission No. 5/2014) and all experiments were conducted according to the latest version of the declaration of Helsinki.

Table 1. Characteristics of study participants separated by Sex

	Males ($n = 10$)	Females ($n = 10$)	All ($n = 20$)
Age (years)	18.3 ± 1.8	17.9 ± 2.8	18.1 ± 2.3
Body height (cm)***	194.9 ± 7.2	180.0 ± 7.4	187.4 ± 10.4
Body composition			
Body mass (kg)***	84.9 ± 6.4	67.0 ± 8.3	76.0 ± 11.7
Body fat (kg) **	6.5 ± 3.2	11.7 ± 3.3	9.1 ± 4.1
Body mass index*	22.4 ± 1.4	20.7 ± 1.6	21.5 ± 1.7
Footedness (left/right)	(0/10)	(1/9)	(1/19)
Training (h/week)	18 ± 5	20 ± 4	19 ± 4

Values are mean ± standard deviation; asterisks indicate significant sex differences (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$).

Experimental procedure

A single-group repeated-measures design was used to assess the acute effects of fatigue on performance variables, blood lactate concentration, and leg muscle activities during jumping (CMJ, DJ) on stable and unstable surfaces.

At the beginning of each testing session, participants had to complete a questionnaire concerning health, training modalities (i.e., h/week, training content), and leg dominance (Coren, 1993). Subsequently, body fat mass was analyzed with the InBody720 (Biospace; Seoul, South Korea). Thereafter, a standardized warm-up protocol was conducted consisting of 5 min of moderate cycling on an ergometer [120 watts (women)/150 watts (men) at 80–90 rpm], 3 min of rope skipping, and 2 min of a familiarization phase with CMJs and DJs. Before and immediately after the fatigue protocol, participants had to perform one set of 3 CMJs and DJs on stable (i.e., force plate only) and unstable surfaces (i.e., AIREX® balance pad: Airex AG, Sins, Switzerland on top of the force plate). Jumps were discarded if the subjects lost balance during ground contact or if the jumping technique was not in accordance with verbal instructions given by the investigator (e.g., hands of hip). If single jump trials were discarded, a maximum of five jumps was conducted. The test sequence of DJs and CMJs on stable/unstable conditions was randomized to avoid potential bias from recovery during post-tests. The same randomized order was applied during pre- and post-tests. Surface compliance of the AIREX® balance pad can be defined by a restitution coefficient of 0.33. The restitution coefficient is a measure of the elasticity of an unstable surface (Ramirez-Campillo et al., 2013).

During the CMJs, participants stood in an upright position on a force plate, feet shoulder-width apart, and hands akimbo. Jumps were initiated with a countermovement immediately followed by a concentric upward movement. The DJ was conducted from a dropping height of 40 cm for both stable and unstable conditions. Participants stood in an upright position on a box, feet shoulder-width apart, with hands akimbo. They were asked to step off the box with their dominant leg, dropped down to land evenly on both feet on the force plate and immediately performed a double-leg vertical jump at maximal effort. Proper care was taken to assure a uniform dropping technique across all subjects (Kibele, 1999). All participants were instructed to jump as high as possible (CMJ, DJ) and to keep ground contact as short as possible during DJs. The same verbal instructions were provided throughout pre- and post-fatigue testing.

Fatigue protocol

Fatigue was induced using a repeated vertical jump protocol. Participants were asked to perform several sets of repetitive double-leg box jumps (box height: 37 cm) with arm swing until failure in each set. In accordance with Wadden et al. (2012), failure/exhaustion was defined as the time when the participant was unable to maintain a given cadence (70 bpm) during box jumping. The number of repetitions in the first set was used as reference for the overall number of sets conducted. More precisely, participants performed as many sets as possible until the number of repetitions in a set was lower than 60% of the number of repetitions during the first set. To obtain the same relative amount of fatigue for each subject, the number of jumps performed during the sets as well as the number of sets performed until failure was different between the subjects. A 60-s rest was provided between sets. The number of repetitions was recorded using an optoelectric photocell system (Optojump Next; Microgate, Bolzano, Italy), which was fixed on the floor.

Assessment of jump performance

All jumps were performed on a one-dimensional force plate system (Leonardo Mechanograph®, Novotec Medical, Pforzheim, Germany), which measures vertical ground reaction force (GRF) separately for the right and left leg. To record the knee angle during jumping, a goniometer (Noraxon®, Scottsdale, Arizona, USA) was attached at the transverse axis of the knee joint of the dominant leg (Coren, 1993). The force signal was used as a trigger to determine ground contact and to average three jumping trials (Prieske et al., 2013). Synchronization of GRF, goniometer, and electromyographic (EMG) data was achieved by analog-to-digital conversion on the same I/O board (TeleMyo 2400R G2 Analog Output Receiver, Noraxon) with a sampling frequency of 1500 Hz.

The GRF signal was used to calculate flight and contact times. Time during ground contact was divided into braking and push-off phase to distinguish between eccentric and concentric muscle actions. For DJs, the braking phase was defined as time interval from the first ground contact of the investigated leg until participants reached their maximum knee flexion angle (Hoffren et al., 2007). In terms of CMJ, the braking phase was defined as time interval from onset of force (i.e., GRF) over baseline level to the maximum knee flexion angle. The push-off phase was defined as time from instant of maximum knee flexion angle to the instant of take-off (Hoffren et al., 2007).

Jump height was calculated using the formula: jump height = $1/8 \times g \times t^2$, where g is the acceleration due to gravity and t is the flight time. In addition, participants' performance index was calculated for the DJ using the following formula: performance index = jump height/contact time (Prieske et al., 2013). The performance index determines the relationship between DJ height and the duration of ground contact, yielding an objective measure of reactive force.

Assessment of leg muscle activities

Surface EMG activity was recorded for six muscles of the dominant leg [m. vastus medialis (VM), m. vastus lateralis (VL), m. biceps femoris (BF), m. tibialis anterior (TA), m. gastrocnemius medialis (GM), and m. soleus (SOL)]. Circular bipolar surface electrodes (Ambu®, type Blue Sensor P-00-S/50, Ag/AgCl, diameter: 13 mm, center-to-center distance: 25 mm, Ballerup, Denmark) were placed on the muscle bellies and aligned parallel to the muscle fibers according to the European recommendations for surface electromyography (Hermens, 1999). A ground electrode was attached medially above the tibial bone. The skin of the electrodes' location were shaved, slightly roughened, degreased and disinfected (Epicont, GE Medical, Freiburg, Germany) to keep the interelectrode resistance below 5 kΩ. Elastic bands, tapes and transparent films (Tegaderm Film, 3M Deutschland GmbH – Health Care Business, Neuss, Germany) were used to fix the electrodes and cables during jumping. EMG signals were amplified, recorded telemetrically at a sampling frequency of 1500 Hz (TeleMyo 2400T G2, Noraxon®) and stored on a computer.

Subsequently, the raw EMG signals were filtered (10–750 Hz bandwidth), full-wave rectified and further analyzed using MyoResearch XP Master Edition software (version 1.08, Noraxon®). Mean average voltage (MAV) were calculated for each muscle during the preactivation phase (i.e., 100 ms prior to instant of ground contact of the investigated leg; DJ only), the braking phase, and the push-off phase (Prieske et al., 2013). MAV values were averaged over three DJ and CMJ trials, and normalized to the respective preactivation phase of the non-fatigued stable condition (Hoffren et al., 2007). Additional time intervals were analyzed during DJs to examine muscle reflex contributions of neuromuscular activation during

DJs. Therefore, iEMG was computed for four distinct intervals: 30–60, 60–90, 90–120, and 120–150 ms after ground contact (Prieske et al., 2013). Of note, iEMG values were normalized to the 30–60 ms interval of the non-fatigued, stable condition (Prieske et al., 2013).

Blood lactate concentration

Blood lactate concentrations were determined using Biosen C_line (EKF-diagnostic GmbH, Barleben, Germany). Capillary blood samples were taken from the cleaned and disinfected earlobe (plastic capillaries; 20 μL) before warm-up (rest value) and after the end of the fatigue protocol. The first blood drop was discarded to avoid contamination.

Rate of perceived exertion

To assess the rate of subjectively perceived exertion during the fatigue protocol, a Borg scale was used (Borg, 1982). Following each set of the fatigue protocol, participants were asked to indicate their level of exertion on a 6–20 Borg scale, with 6 indicating no exertion at all and 20 indicating maximal exertion.

Statistical analyses

Data are presented as group mean values ± standard deviations (SD). After data were tested for normal distribution (i.e., Kolmogorov–Smirnov test), a 2 (sex: male, female) × 2 (Fatigue: non-fatigued, fatigued) × 2 (Surface: stable, unstable) analysis of variance (ANOVA) with repeated measures on Fatigue and Surface was applied to analyze jump performance and leg muscle activities. For analyses of blood lactate concentration and subjectively perceived exertion during fatigue, a 2 (Sex: male, female) × (Fatigue: non-fatigued, fatigued) ANOVA with Fatigue as repeated within-subject factor was computed. To elucidate potential sex effects on subjects' characteristics, a one factor (Sex: male, female) ANOVA was calculated. The significance level was set at α level < 0.05.

In addition, the classification of effect sizes was determined by converting partial eta-squared (η_p^2) to Cohen's *d*. Effect sizes characterize the effectiveness of an intervention and are used to determine whether a difference is a difference of practical importance. According to Cohen (1988), effect sizes can be classified as small ($0.00 \leq d < 0.50$), medium ($0.50 \leq d < 0.80$), and large ($d \geq 0.80$). All analyses were performed using Statistical Package for Social Sciences (SPSS) version 22.0 (SPSS Inc., Chicago, Illinois, USA).

Results

Our experimental protocol did not cause any test or fatigue-related injuries. The inclusion of the factor Sex in our statistical model did not produce any significant interactions for measures of jump performance and leg muscle activities which is why we decided to present mean values for males and females in the following.

Fatigue protocol

On average, our participants endured the fatigue protocol for 519 ± 200 s (range: 200–1209 s). During that time, athletes performed a mean of 4 ± 2 sets (range: 2–7 sets), which corresponds to an overall number of double-leg box jumps of 205 ± 95 (range: 96–482 jumps). Blood lactate concentration increased significantly from an initial resting value of 1.1 ± 0.6 mmol/L (range: 0.5–2.8 mmol/L) to 8.5 ± 3.1 mmol/L (range: 4.1–15.2 mmol/L) immediately after termination of the fatigue protocol ($P < 0.001$).

At the end of the fatigue protocol, mean subjective level of exertion amounted to 19.4 ± 1.0 on the Borg Scale, which is indicative of an extremely hard perceived exertion (Chen et al., 2013).

Effect of fatigue on jump performance and leg muscle activities

In terms of jump performance, fatigue resulted in significant decreases in DJ height (–7%; $P < 0.001$; $d = 2.82$) and performance index (−13%; $P < 0.001$; $d = 2.77$) as well as in an increases in time of braking (6%; $P < 0.05$; $d = 1.34$) and push-off phase (6%; $P < 0.05$; $d = 1.34$) during DJs (Table 2). With regard to CMJ, a significant decline in jump height was observed (–3%; $P < 0.05$; $d = 1.14$).

Concerning leg muscle activities, the fatigue protocol produced significant decreases in BF and TA activities during the preactivation phase (12–19%, $P < 0.01$, $1.42 \leq d \leq 2.46$), in VL, BF, TA, GM, and SOL activities during the braking phase (7–14%, $P < 0.05$, $1.36 \leq d \leq 2.56$), as well as in GM and SOL activities during the push-off phase (7–11%, $P < 0.01$, $1.46 \leq d \leq 1.70$) during DJs (Fig. 1). In addition, the analyses of 30 ms time intervals following ground contact during DJs revealed significant decreases in VM, VL, TA, GM, and SOL activities during the 30–60 ms time interval (6–18%, $P < 0.05$, $1.06 \leq d \leq 1.98$), in VL, BF, TA, GM, and SOL activities during the 60–90 ms time interval (2–27%, $P < 0.05$, $1.08 \leq d \leq 2.22$), in BF, GM, and SOL activities during the 90–120 ms time interval (17–22%, $P < 0.05$, $1.26 \leq d \leq 3.18$), and in BF, TA, and GM activities during the 120–150 ms time interval (5–24%, $P < 0.05$, $1.18 \leq d \leq 1.86$) (Table 3). For CMJ, fatigue resulted in significant decreases in VL, BF, and TA activities during the braking phase (5–24%, $P < 0.05$, $0.59 \leq d \leq 1.05$), as well as in BF, TA, GM, and SOL activities during the push-off phase (8–10%, $P < 0.05$, $0.64 \leq d \leq 1.25$) (Fig. 2).

Table 2. Variables of drop and countermovement jump performance separated by Fatigue and Surface

	Non-fatigued				Fatigued				Surface × Fatigue		Surface			Fatigue		
	Stable		Unstable		Stable		Unstable									
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*	*d*	Δ (%)	*P*	*d*	Δ (%)	*P*	*d*
Drop jump																
Jump height (cm)	28.2	4.3	26.2	5.3	26.4	3.9	24.1	4.4	0.441	0.38	−8	0.001	1.90	−7	0.000	2.82
Time for braking phase (ms)	103.4	9.5	116.0	8.4	109.2	12.0	122.4	15.7	0.836	0.10	12	0.000	2.90	6	0.011	1.34
Time for push-off phase (ms)	111.9	17.9	111.7	19.3	118.6	19.4	118.9	18.6	0.807	0.12	0	0.997	0	6	0.011	1.34
Performance index (m/s)	1.3	0.3	1.2	0.3	1.2	0.2	1.0	0.3	0.743	0.16	−12	0.000	2.74	−13	0.000	2.77
Countermovement jump																
Jump height (cm)	32.4	5.4	31.8	6.2	31.2	5.3	31.2	5.5	0.291	0.52	−1	0.373	0.44	−3	0.026	1.14
Time for braking phase (ms)	226.8	55.2	217.4	49.6	222.2	53.6	217.7	54.9	0.744	0.16	−2	0.322	0.48	−1	0.754	0.14
Time for push-off phase (ms)	257.3	49.0	264.4	41.2	250.3	37.0	258.6	52.2	0.905	0.06	1	0.246	0.56	−2	0.349	0.46

Values are mean ± standard deviation.*d*, effect size Cohen's *d*; SD, standard deviation.

Effect of surface instability on jump performance and leg muscle activities

In terms of jump performance, surface instability resulted in significantly lower DJ height (−8%; $P < 0.01$; $d = 1.90$) and performance index (−12%; $P < 0.001$; $d = 2.74$) and significantly higher time for braking phase (12%; $P < 0.001$; $d = 2.90$). Surface instability did not have any significant effect on performance measures during CMJ (Table 2).

Concerning leg muscle activities, surface instability resulted in significantly lower TA, GM, and SOL activities during the preactivation phase (11–17%, $P < 0.01$, $1.76 \leq d \leq 2.54$), and in significantly lower VM and BF activities during the braking phase (10–14%, $P < 0.01$, $1.38 \leq d \leq 1.46$), as well as in lower VM, VL, and SOL activities during the push-off phase (10–25%, $P < 0.05$, $1.08 \leq d \leq 1.54$) during DJs (Fig. 1).

Moreover, the analyses of fixed 30 ms time intervals during DJs revealed significantly lower VM, VL, BF, and SOL activities during the 30–60 ms time interval (9–17%, $P < 0.05$, $1.36 \leq d \leq 2.20$), as well as in BF during the time intervals 60–90 ms (24%, $P < 0.01$, $d = 1.72$), 90–120 ms (25%, $P < 0.05$, $d = 1.42$), and 120–150 ms (19%, $P < 9.05$, $d = 1.20$; Table 3). For CMJs, surface instability resulted in significantly lower SOL activity (7%, $P < 0.05$, $d = 1.20$) during the push-off phase (Fig. 2).

Interaction of Fatigue and Surface on jump performance and leg muscle activities

No statistically significant Surface × Fatigue interactions were found for any of the jump performance outcomes (Table 2).

In terms of leg muscle activities, hardly any statistically significant Surface × Fatigue interactions were found for lower limb muscle activities during DJs, except for the TA during preactivation phase ($P < 0.05$; $d = 1.08$), the VM during the 90–120 ms interval ($P < 0.05$; $d = 1.22$), and the BF during the 120–150 ms interval ($P < 0.05$; $d = 1.10$). In terms of CMJ, no statistically significant Surface × Fatigue interactions were found for lower limb muscle activity.

Discussion

To the authors' knowledge, this is the first study to examine the effects of fatigue and surface instability on performance measures and leg muscle activities during DJs and CMJs in healthy young elite athletes. The main results of this study can be summarized as follows: (a) fatigue produced significantly lower jump performance and leg muscle activities during DJs and CMJs, (b) surface instability resulted in significantly lower jump performance and leg muscle activities during DJ but not

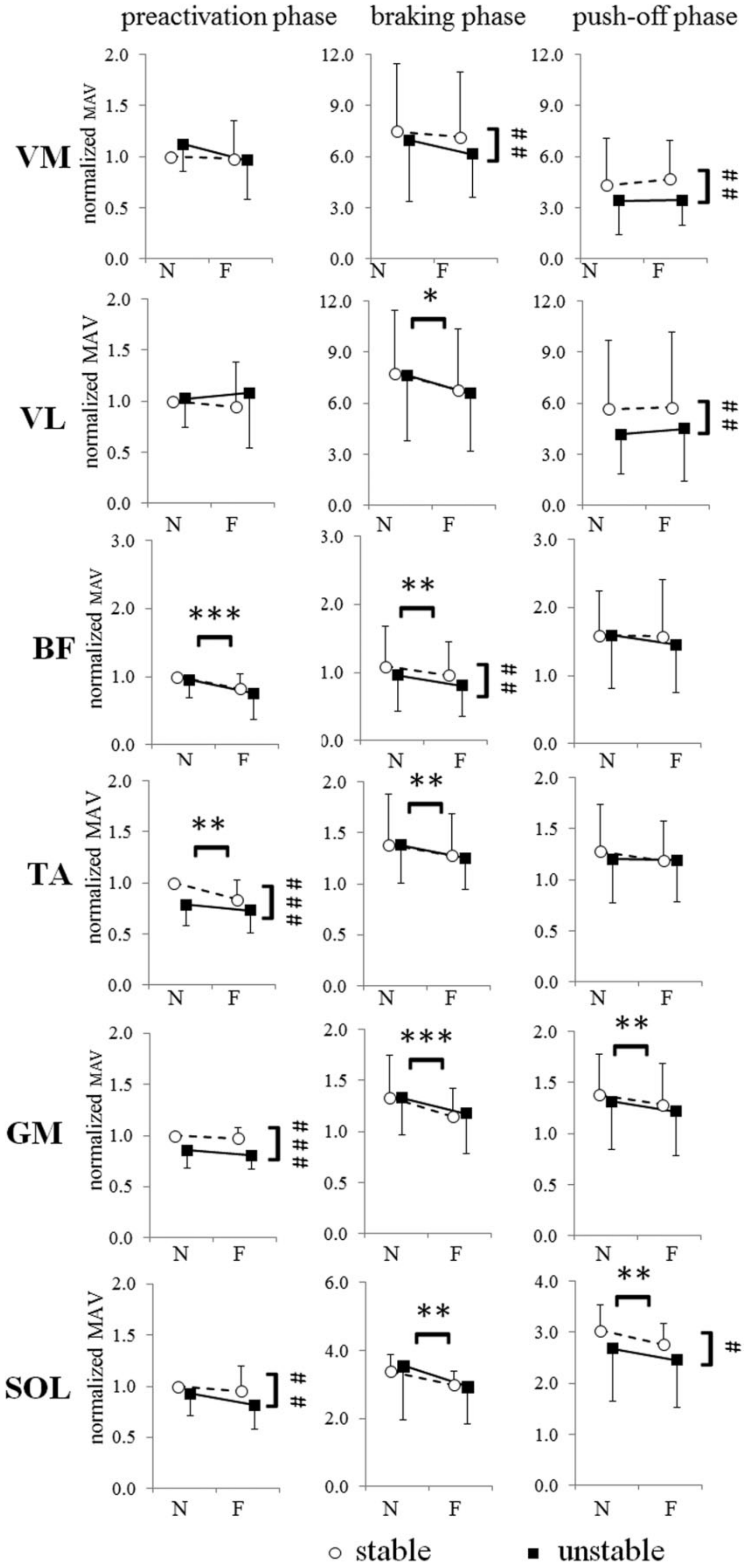
preactivation phase
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Fig. 1. Leg muscle activity during drop jumps. Mean average voltage (MAV) values were normalized to the preactivation phase of drop jumps (stable and non-fatigued condition). Please note that for better visual illustration, the vertical axes were not scaled similarly in all instances. BF, musculus biceps femoris; F, fatigued condition; GM, musculus gastrocnemius medialis; N, non-fatigued condition; SOL, musculus soleus; TA, musculus tibialis anterior; VL, musculus vastus lateralis; VM, musculus vastus medialis; $^{\#}$main effects of Surface ($^{\#}P < 0.05$; $^{\#\#}P < 0.01$; $^{\#\#\#}P < 0.001$); *main effects of Fatigue (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$). Values are means and standard deviations.

Table 3. Leg muscle activities during drop jumps in time intervals of 30–60, 60–90, 90–120, and 120–150 ms after ground contact

Drop jump		Non-fatigued				Fatigued				Surface × Fatigue		Surface			Fatigue		
		Stable		Unstable		Stable		Unstable									
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*	*d*	Δ (%)	*P*	*d*	Δ (%)	*P*	*d*
30–60 ms	VM	1	0	0.86	0.28	0.78	0.23	0.70	0.22	0.405	0.42	–9	0.012	1.42	–18	0.001	1.98
	VL	1	0	0.88	0.22	0.88	0.28	0.69	0.22	0.413	0.40	–17	0.000	2.20	–15	0.015	1.32
	BF	1	0	0.82	0.35	1.01	0.43	0.85	0.44	0.978	0.02	–16	0.012	1.36	2	0.710	0.18
	TA	1	0	1.09	0.28	0.94	0.21	0.95	0.23	0.311	0.52	7	0.325	0.50	–11	0.009	1.48
	GM	1	0	0.90	0.30	0.89	0.29	0.81	0.29	0.744	0.16	–9	0.102	0.82	–11	0.007	1.44
	SOL	1	0	0.88	0.20	0.90	0.25	0.76	0.34	0.806	0.12	–9	0.012	1.42	–6	0.049	1.06
60–90 ms	VM	1.05	0.31	1.16	0.33	1.09	0.51	1.07	0.40	0.265	0.56	5	0.544	0.30	–3	0.812	0.12
	VL	1.29	0.44	1.24	0.27	1.05	0.39	1.04	0.35	0.699	0.18	–3	0.604	0.24	–17	0.017	1.24
	BF	2.14	0.85	1.75	0.86	1.70	0.82	1.16	0.35	0.467	0.36	–24	0.002	1.72	–27	0.000	2.22
	TA	0.96	0.33	1.08	0.33	0.93	0.36	0.98	0.28	0.350	0.46	13	0.101	0.84	–2	0.040	1.08
	GM	1.46	0.43	1.52	0.54	1.19	0.39	1.33	0.45	0.349	0.46	8	0.072	0.90	–15	0.001	1.80
	SOL	1.69	0.56	1.60	0.61	1.36	0.59	1.45	0.54	0.087	0.88	1	0.966	0.02	–18	0.002	1.80
90–120 ms	VM	1.04	0.52	0.89	0.45	0.98	0.48	1.00	0.51	0.018	1.22	–6	0.332	0.46	3	0.709	0.18
	VL	1.20	0.49	1.15	0.43	1.05	0.54	0.98	0.41	0.937	0.04	–5	0.228	0.58	–14	0.101	0.82
	BF	2.67	1.51	2.27	1.33	2.50	1.39	1.62	0.68	0.052	0.98	–25	0.008	1.42	–17	0.015	1.26
	TA	0.94	0.31	1.00	0.36	0.91	0.30	0.93	0.35	0.457	0.36	6	0.516	0.32	–2	0.216	0.62
	GM	1.49	0.36	1.50	0.42	1.22	0.36	1.22	0.42	0.970	0.02	4	0.891	0.06	–17	0.000	2.62
	SOL	1.71	0.57	1.83	0.69	1.43	0.57	1.37	0.46	0.257	0.56	11	0.776	0.14	–22	0.000	3.18
120–150 ms	VM	0.69	0.42	0.69	0.46	0.80	0.51	0.80	0.36	0.942	0.04	0	0.986	0.00	16	0.110	0.80
	VL	0.72	0.39	0.77	0.35	0.74	0.47	0.83	0.36	0.528	0.30	9	0.310	0.50	5	0.682	0.20
	BF	3.50	2.07	3.28	1.86	3.09	1.99	2.06	1.32	0.032	1.10	–19	0.021	1.20	–24	0.001	1.86
	TA	1.10	0.45	1.00	0.33	0.92	0.34	0.95	0.29	0.124	0.78	–3	0.724	0.18	–9	0.004	1.62
	GM	1.66	0.66	1.64	0.57	1.53	0.54	1.40	0.61	0.202	0.64	–5	0.350	0.46	–5	0.026	1.18
	SOL	1.54	0.75	1.52	0.72	1.44	0.70	1.41	0.60	0.891	0.06	9	0.771	0.14	–9	0.092	0.86

Values are mean ± standard deviation. Data are reported for main effects of Surface and Fatigue and Surfaxe × Fatigue interactions. IEMG values were normalized on stable non-fatigued 30 -60 ms interval of drop jumping. BF, musculus biceps femoris; *d*, effect size Cohen's *d*; GM, musculus gastrocnemius medialis; SD, standard deviation; SOL, musculus soleus; TA, musculus tibialis anterior; VM, musculus vastus medialis; VL, musculus vastus lateralis.

during CMJ, and (c) the fatigue-related decline in DJ and CMJ performance was not additionally modulated by surface instability.

Effects of fatigue on jump performance and leg muscle activities

Repetitive SSC actions are associated with fatigue and, consequently, acute performance decrements (Komi, 2002). In terms of repetitive vertical jumps, our results revealed a fatigue-related decline in subsequent DJ (jump height: 7%, performance index: 13%) and CMJ performance (jump height: 3%). These findings are well in line with previous study findings. For instance, regarding DJ, studies investigating the effects of repetitive free vertical jumps found declines in the subsequent DJ height of about 7–12% (Hortobagyi et al., 1991; Skurvydas et al., 2002). In terms of CMJ, previous studies even reported fatigue-related declines in jump height of 7–44% following repetitive vertical jumps (Skurvydas et al., 2000, 2002; Rodacki et al., 2001). It seems reasonable to argue that the higher decrements in CMJ performance reported in the literature as compared with the present study may partly be attributed to methodological reasons. In fact, the subjects in the studies of Rodacki et al. (2001) as well as Skurvydas et al. (2000) performed repetitive maximal CMJs, whereas the present study investigated the effect of repetitive double-leg box jumps during the fatigue protocol on DJ and CMJ performance. Thus, the magnitude of CMJ performance following fatigue appears to depend on the exercise of the fatigue protocol (i.e., box jumps vs CMJ).

In accordance with our findings regarding jump performance, significantly decreased leg muscle activity was found during DJs and CMJs under fatigued compared with non-fatigued conditions. With regard to the effects of different SSC fatigue protocols (e.g., continuous CMJ, DJ in sledge apparatus, sprints) on subsequent

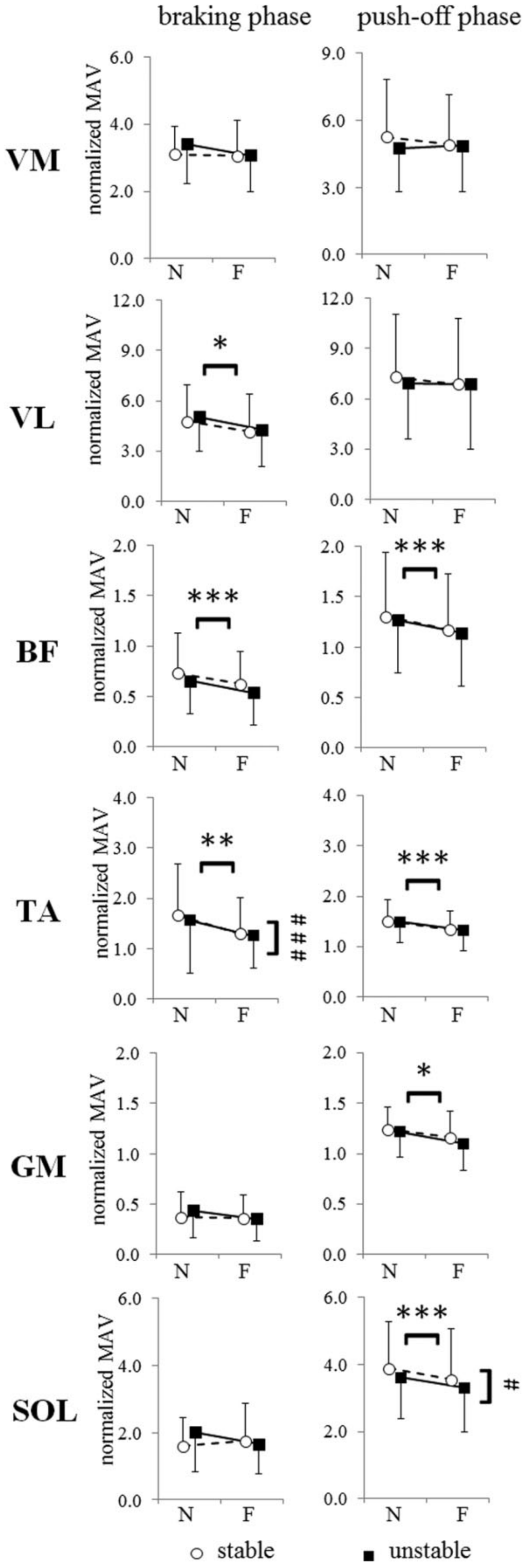

Fig. 2. Leg muscle activity during countermovement jumps. Mean average voltage (MAV) values were normalized to the preactivation phase of drop jumps (stable and non-fatigued condition). Please note that for better visual illustration, the vertical axes were not scaled similarly in all instances. BF, musculus biceps femoris; F, fatigued condition; GM, musculus gastrocnemius medialis; N, non-fatigued condition; SOL, musculus soleus; TA, musculus tibialis anterior; VL, musculus vastus lateralis; VM, musculus vastus medialis; $^{\#}$main effects of Surface ($^{\#}P < 0.05$; $^{\#\#}P < 0.01$; $^{\#\#\#}P < 0.001$); *main effects of Fatigue ($^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$). Values are means and standard deviations.

maximal vertical jumps, previous studies showed lower leg muscle activity following fatiguing exercises (McNeal et al., 2010; Bobbert et al., 2011). In terms of repetitive vertical jumps, our analyses revealed a significant decline in leg muscle activity during the preactivation, braking and push-off phases of DJs and CMJs, respectively. Particularly during the braking phase of DJs, decreases in muscle activity (7–14%, $P < 0.05$, $1.36 \leq d \leq 2.56$) were found for almost all leg muscles tested (i.e., VL, BF, TA, GM, SOL). Thereby, we confirmed that repetitive vertical jumps resulted in decreased neuromuscular activity, particularly during the eccentric phase of subsequent maximal vertical jumps utilizing fast SSC muscle actions (< 230 ms). Because of lower leg muscle activity in the braking phase, muscle stiffness decreases and simultaneously diminishes the efficacy of SSC actions (Arampatzis et al., 2004). To achieve maximal recoil of elastic strain energy during the push-off phase, leg stiffness has to be high during the braking phase (Avela et al., 1996), thereby depending on passive (anatomical) stiffness, muscle stiffness (muscle activation), muscular co-contraction as well as on stretch reflex-induced muscle activity (sensitivity of muscle spindle).

The origin of the fatigue-induced decreases in leg muscle activity can be versatile (i.e., central or peripheral). In the present study, significant increases in blood lactate concentration were found immediately after termination of the fatigue protocol (8.5 ± 3.1 mmol/L) compared with the initial resting value (1.1 ± 0.6 mmol/L) indicating muscular fatigue with peripheral origin (Grassi et al., 2015). Nevertheless, we additionally investigated specific time intervals after instant of ground contact which are commonly associated with stretch reflex-induced muscle activation during DJs (i.e., short latency response, medium latency response, long latency response 1 and 2) (Taube et al., 2008). In this regard, Taube et al. (2008) highlighted that the early interval (i.e., 30–60 ms) is under spinal and the later intervals (i.e., 90–120 ms, 120–150 ms) are under supraspinal control. Our results showed a statistically significant reduction of leg muscle activity in the early 30–60 ms (i.e., VM, VL, TA, GM, SOL) and the late 90–120 ms (i.e., BF, GM, SOL) as well as in the 120–150 ms time intervals (i.e., BF, TA, GM). Consequently both central (i.e., neural) as well as peripheral (i.e., muscular) mechanisms may have contributed to the reduction in leg muscle activity under fatigued conditions.

Effects of surface instability on jump performance and leg muscle activities

Vertical jumps often occur on relatively unstable surfaces during training and/or competition. In particular in volleyball, different artificial (e.g., balance pad) or natural unstable surfaces (e.g., sand, grass) change movement conditions and demands for athletic performance. So far, only few studies investigated the effects of unstable surface conditions during DJs and CMJs (Arampatzis et al., 2004; Prieske et al., 2013; Howard et al., 2015). Recently, Prieske et al. (2013) examined the effects of surface instability (i.e., AIREX® balance pad) on DJ performance in healthy male and female young adults (23 ± 3 years). The authors found an instability-related lower DJ height (9%) and performance index (12%). The present study confirmed these findings (i.e., lower DJ height: 8%, lower performance index: 12%) by using the same unstable surface (i.e., AIREX® balance pad). In contrast, Arampatzis et al. (2004) observed an increase in DJ height (7%) in healthy, female gymnasts when performing DJs on compliant versus stable sprung surfaces. This indicates that the effect of surface condition depends on the mechanical properties of the unstable surfaces (e.g., thickness, stiffness, compliance). More precisely, force and/or power output will be lower the higher the level of surface instability (Saeterbakken & Fimland, 2013). Besides the discrepancy between the effects on surface instability on DJ performance, inconsistency was also found in the literature for CMJ performance on unstable compared with stable surfaces. For instance, Howard et al. (2015) investigated the effects of back extensor fatigue on jump performance and neuromuscular performance during CMJ and lateral jumps on unstable (i.e., AIREX® balance pad) compared with stable surface in healthy males (23 ± 5 years). Their study revealed no main effect of surface instability on measures of CMJ performance. In contrast, Bishop (2003) examined healthy male and female beach volleyball players (23 ± 3 years) and found significant performance decrements in CMJ height (6%) and spike jump height (15%) when jumping on unstable (i.e., sand) compared with stable surfaces.

Further, the present findings indicate that leg muscle activity was significantly lower under unstable compared with stable conditions during DJs, but not during CMJs (except for SOL). There is a controversy in the literature regarding the effects of surface condition on leg muscle activity. In fact, whereas some research groups found significantly higher leg muscle activity during lower limb exercises (e.g., squats) on unstable compared with stable surfaces (Anderson & Behm, 2005), others demonstrated similar (Li et al., 2013; Márquez et al., 2014) or significantly lower activation levels (McBride et al., 2006; Prieske et al., 2013). In terms of maximal jumping, Prieske et al. (2013) reported significantly lower leg muscle activity during the preactivation (i.e., 21–24% in TA and GM), braking (i.e., 15% in VM), and push-off phase (i.e., 11–21% in VM and GM) in healthy, physically active subjects (23 ± 3 years) when performing DJs on unstable (i.e., AIREX® balance pad) compared with stable surfaces. Accordingly, the present study found significantly lower leg muscle activation levels during the preactivation (i.e., 11–17% in TA, GM, and SOL), braking (i.e., 10–14% in VM and BF), and push-off phase (i.e., 10–25% in VM, VL, and SOL) of DJs on unstable compared with stable surfaces.

It has been argued that complex movements such as DJs are mostly preprogrammed and controlled by higher supraspinal centers (Avela et al., 1996). Therefore, leg muscle activity occurring before ground contact in DJ might represent a feedforward activation pattern that prepares the muscles for higher loads during ground contact. Hence, lower activation levels during the preactivation phase might indicate a modified feedforward activation pattern when performing DJs on unstable compared with stable surfaces. During ground contact of jumping, peripheral feedback is used to modify preprogrammed activation patterns (Avela et al., 1996). In terms of the fixed time intervals during ground contact, the present findings revealed lower iEMG levels with surface instability particularly in the 30–60 ms interval (i.e., VM, VL, BF, and SOL). Thus, our results indicate that the instability-related lower leg muscle activity during ground contact of DJs may specifically be altered in time intervals that are associated with spinal stretch reflex-induced activity.

In terms of CMJ, surface instability did not affect leg muscle activity (except for SOL MAV during the push-off phase). This is in line with findings of a recent study investigating the effect of lower back fatigue on CMJ and lateral jump performance on stable and unstable surfaces (i.e., AIREX® balance pad) in healthy, physically active males (23 ± 5 years; Howard et al., 2015). It appears that unstable surfaces such as those used in the present study do not alter neuromuscular control during CMJs compared with stable conditions. Given that leg muscle activity was modified by surface condition during DJs but not during CMJs, it can be speculated that the effect of surface instability on leg muscle activity during jumping is not only dependent on the mechanical properties of the surface, but also modulated by the movement task and the inherent control strategy. DJs are highly dynamic movements with fast SSC actions (< 230 ms). These actions are characterized by an anticipatory modulation before ground contact to properly adjust the motor system (e.g., stiffness regulation) as well as to prepare the leg muscles for the oncoming load and possible postural perturbations (Avela et al., 1996). Thus, lower leg muscle activity during DJs may represent an instability-related anticipatory down-regulation of the leg muscles, causing the decline in DJ performance. In contrast, CMJs are characterized by slow SSC actions (> 230 ms) and are performed when already standing on the specific surface. Therefore, the missing instability-related decline in performance/leg muscle activity during CMJs in the present study may be attributed to the less anticipating amount of motor control and/or an insufficient level of instability, when initiating the jump from an upright standing position on the unstable surface.

Interaction of Fatigue and Surface on jump performance and leg muscle activities

In contrast to our hypothesis, no Surface × Fatigue interactions were found for DJ and CMJ performance. This indicates that jump performance of jump-trained athletes is not additionally affected by a moderately unstable surfaces following fatigue. In terms of the effect of surface condition following fatigue, a recent study of Bisson et al. (2014) investigated the effect of fatiguing isometric contraction of the plantar flexors on postural control (i.e., static steady-state balance) on stable and unstable surfaces in 11 healthy young (24 ± 4 years) and 13 healthy older subjects (65 ± 4 years). Of note, postural control can be considered as important component for maximal jumping (Granacher et al., 2010). In the study of Bisson and colleagues (2014), it was found that the effect of fatigue on postural control was more pronounced on unstable compared with stable surfaces particularly in older adults because of the less efficient proprioceptive and neuromuscular system. Given that jump-trained elite athletes participated in the present study, the lack of Surface × Fatigue interaction could be explained by a less demanding instability level (i.e., AIREX© balance pad) for the highly efficient neuromuscular system of the subjects.

In accordance with our findings on jump performance, no statistically significant Surface × Fatigue interaction was found for measures of leg muscle activity during DJs and CMJs (except for TA during preactivation phase, VM during the 90–120 ms interval, and BF during the 120–150 ms interval). Consequently, neuromuscular deteriorations caused by jump fatigue are not additionally affected by moderately unstable surface in jump-trained elite athletes.

Perspectives

Artificial surface instabilities (e.g., balance pads) are frequently used during athletic training and rehabilitation in order to mimic the demands of the respective sport-specific activity (Behm & Sale, 1993). Thus, it is crucial to know how neuromuscular performance is modulated by surface instability under fatigued conditions caused by competition and/or training regimes in high-level athletes. The present findings demonstrated that repetitive jumping negatively affects DJ (i.e., jump height, performance index) and CMJ performance (i.e., jump height) and leg muscle activity during the preactivation (i.e., DJs), braking, and push-off phases (i.e., DJs, CMJs), irrespective of surface condition. Further, performance output (i.e., jump height, performance index) and leg muscle activities were lower during DJs on unstable compared with stable surfaces, irrespective of fatigue. Of note, fatigue-induced performance changes during jumping were not additionally affected in jump-trained elite athletes (i.e., volleyball players) when jumping on moderately unstable surfaces (i.e., AIREX® balance pad). Based on our findings, it can be speculated that plyometric exercises conducted under non-fatigued condition on stable surfaces may provide the most effective stimulus for enhancing jump performance during plyometric training.

Key words: Exhaustion, stretch-shortening cycle, jump height, EMG, athlete.

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