

## The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training

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Accepted for publication 23 December 2010

There is an ongoing discussion about how to improve jump performance most efficiently with plyometric training. It has been proposed that drop height influences the outcome, although longitudinal studies are missing. Based on cross-sectional drop jump studies showing height-dependent Hoffmann (H)-reflex activities, we hypothesized that the drop height should influence the neuromuscular activity and thus, the training result. Thirty-three subjects participated as a control or in one of two stretch-shortening cycle (SSC) interventions. Subjects either trained for 4 weeks doing drop jumps from 30, 50, and 75 cm drop heights (SSC1) or completed the same amount of jumps exclusively from 30 cm (SSC2). During training and testing (from 30, 50, and 75 cm), subjects were instructed to minimize the duration of ground contact and to maximize their rebound height. Rebound heights were significantly augmented after

SSC1, but a trend was only observed after SSC2. In contrast, the duration of ground contact increased after SSC1 but decreased after SSC2. The performance index (rebound height/duration of ground contact) improved similarly after SSC1 (+14%) and SSC2 (+14%). Changes in performance were accompanied by neuromuscular adaptations: for SSC1, activity of the soleus increased toward take-off (between 120 and 170 ms after touchdown), whereas SSC2-trained subjects showed enhanced activity shortly after ground contact (20–70 ms after touch down). The present study demonstrates a strong link among drop height, neuromuscular adaptation, and performance in SSC training. As the improvement in the performance index was no different after SSC1 or SSC2, the decision whether to apply SSC1 or SSC2 should depend on the specific requirements of the sports discipline.

In many sports disciplines, jump performance in general, and vertical jumping height and duration of ground contact time in particular, is considered as key qualifications. To improve jump performance, training interventions including stretch-shortening cycle (SSC) movements (Markovic, 2007) are regarded as being superior to exercise protocols like heavy and explosive resistance training (Wilson et al., 1993, 1996), electrostimulation (Malatesta et al., 2003) or vibration training (Cardinale & Bosco, 2003), which do not involve SSC contractions. Nevertheless, there exists a great variation in the outcome of SSC training protocols (Markovic, 2007). Part of this variation is thought to be due to differences in the jumping technique and the drop height applied during training (Bobbert et al., 1987a, 1987b; Bobbert, 1990), although longitudinal studies addressing this issue are missing. Furthermore, jumping technique (e.g. the extent of countermovement, time of ground contact, muscular activation pattern) and drop height were most often separately treated (Bobbert et al., 1987a, 1987b; Hunter & Marshall, 2002), even though cross-sectional studies have demonstrated that the drop height influences

the neuromuscular activity and thus, the jumping technique (Komi & Gollhofer, 1997; Leukel et al., 2008a, 2008b). These cross-sectional studies further highlighted that the muscular activity shortly after ground contact at the time of the short latency response (SLR) is particularly influenced by the drop height. When subjects were asked to perform drop jumps from different drop heights, the muscular activity at the SLR was lower in drop jumps from greater heights (80 cm) than from low heights (30 cm) (Komi & Gollhofer, 1997). In a subsequent experiment, the size of the Hoffmann (H)-reflex was found to be inversely related to the drop height (Leukel et al., 2008a, 2008b). The decreased muscular activity and H-reflex excitability at greater heights were argued to be caused by a prevention strategy in order to reduce stress on the tendo-muscular system in high-load conditions.

Recently, Zuur et al. (2010) confirmed the long-held assumption of stretch-induced reflex activity at the time of the SLR in hopping. The authors altered the time of ground contact by changing the height of the floor surface, while subjects were airborne and unaware of this procedure. The latency of the SLR

was exactly time-locked to the instant of ground contact resulting in prolonged latencies in the condition where the landing surface was lowered (due to the longer air time) and in shortened latencies where the landing surface was raised. In SSC movements, these stretch reflex contributions are considered to be an important factor in the ability to transfer energy from the pre-activated and eccentrically stretched muscle–tendon complex to the concentric push-off phase (Dietz et al., 1979; Gollhofer et al., 1992; Voigt et al., 1998b).

As spinal stretch reflexes and H-reflexes are dependent on the drop height (Komi & Gollhofer, 1997; Leukel et al., 2008a) and reflexes influence the stiffness characteristics of the tendo-muscular complex (Hoffer & Andreassen, 1981; Hobara et al., 2007), it was hypothesized that training from different drop heights should induce specific neuromuscular adaptations, which in turn influence the jumping technique; more specifically, the resulting muscular activity at the SLR during drop jumps from low heights (30 cm; Komi & Gollhofer, 1997) was hypothesized to result in a higher muscular stiffness and therefore an improved capacity to store elastic energy when this pattern is reinforced by exercise. This increased muscular stiffness should also enable subjects to minimize their time of ground contact. On the other hand, SSC training incorporating high drop heights was expected to induce adaptations in the concentric rather than the eccentric phase due to the previously observed load-dependent electromyogram (EMG) and H-reflex inhibition at the SLR. Emphasis on the concentric action was assumed to prolong the ground contact times due to an expected reduction in muscular stiffness. The aim of the present study was to identify the influence of the drop height on jump performance by testing the aforementioned hypotheses. For this purpose, two plyometric training protocols were applied; in SSC1, subjects performed drop jumps from high and low drop heights (30, 50, 75 cm), whereas the SSC2 training group jumped solely from a low height (30 cm). Neurophysiological (surface EMG, H-reflexes) and biomechanical parameters (kinematic data, ground reaction force, and rebound height) were used to indicate training-related changes. The relationship between muscular activity and muscular stiffness could not be directly assessed as the length of the muscle fascicles was not monitored. However, before and after training, the ankle joint stiffness was calculated, which is considered to be strongly dependent on the muscular stiffness of the triceps surae.

## **Materials and methods**

### **Subjects**

Thirty-three healthy subjects with no history of neurological disorders or injuries to the lower extremities volunteered to

participate in this study. All subjects participated in sporting activities containing jumps (volleyball, basketball, athletics, etc.) to minimize variations in jumping performance and guarantee high fatigue resistance during the measurements. Thirty-three subjects were randomly allocated into a SSC group training from low (LH; 30 cm), moderate (MH; 50 cm) and high (HH; 75 cm) heights (SSC1; four females and seven males;  $24 \pm 3$  years, weight:  $68 \pm 11$  kg, height:  $177 \pm 9$  cm), a second training group training exclusively from LH (SSC2; four females and seven males;  $25 \pm 4$  years, weight:  $69 \pm 8$  kg, height:  $179 \pm 9$  cm) and a control group (CON; six females and five males;  $24 \pm 3$  years, weight:  $63 \pm 9$  kg, height:  $173 \pm 7$  cm). None of the subjects participated in any other systematic training during the experiment or had performed previously a similar SSC training. All subjects gave written informed consent to the experimental procedure, which was in accordance with the Declaration of Helsinki and approved by the ethics committee of the Albert-Ludwigs-University in Freiburg.

### **SSC1 and SSC2 training**

SSC training was performed three times per week for 4 weeks (12 training sessions), which were all surveyed and supervised by the authors of the study. Each training session lasted for 45–60 min including a 10-min warm up (jogging, mobilization exercises for the trunk muscles and hopping). The SSC1 exercises consisted of drop jumps from three different heights: 30, 50, and 75 cm. Twelve jumps were performed in each training session from 30 and 50 cm, respectively. From the 75 cm height, the number of jumps was successively increased from six drop jumps in the first week to 8 (second week), 10 (third week), and finally 12 jumps (fourth week) to accustom the subjects to the strong impact. The sequence of the three dropping heights was randomized during the training. The SSC1 training was not exclusively restricted to high drop heights, as this would have put too much stress on the tendo-muscular system of the participating subjects. It was considered to be more important that the subjects performed the same amount of jumps in the two training regimes in order to compare both interventions. Furthermore, the amount of jumps was chosen to resemble a realistic training session. In the SSC2 group, subjects performed the same total amount of jumps as the SSC1 group but they jumped solely from LH. All subjects were instructed to perform highly concentrated jumps with maximal intensity, i.e. with minimum duration of ground contact and maximal rebound height. Subjects had to rest 10 s after each jump and 10 min after they completed all jumps from one drop height (SS1) or, in the SS2 group, after 12 (first round) and 24 jumps (second round) from the LH condition. The number of jumps in the last round in the SSC2 group was dependent on the number of jumps subjects of the SSC1 group performed at the HH. Thus, the number of jumps was successively increased from 6 to 12 jumps. Subjects of the control group maintained their normal physical activities throughout the experimental period and were measured again 4 weeks after their initial test.

### **General experimental procedure**

The experiments were conducted before and after the training period. The post-measurement occurred approximately 48 h after the last training session in order to avoid fatigue.

The testing procedure resembled previously reported ones (Leukel et al., 2008a; Taube et al., 2008) and consisted of a 5-min warm-up (low height hopping) to accustom the subjects to the jumping procedure. Before each jump, both hands had to be held akimbo (hands at the ilium), the left leg remained

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stable in order to secure an upright stance whereas the right leg was lifted and projected in front of the body. The jump off was performed with the left leg to keep the right leg (from which the muscular activity was recorded) relaxed until jump off. Subjects were asked to touch down on both feet and to jump off the ground as quickly as possible. Subjects were also instructed to keep this jumping procedure similar throughout the whole experiment. Drop jumps were performed from three different falling heights: low (LH, 30 cm), moderate (MH, 50 cm), and high (HH, 75 cm). From each drop height (30, 50, and 75 cm), five jumps with maximal intensity were performed to measure the maximal individual jump height. Additionally, 10 jumps at submaximal intensity without peripheral nerve stimulation were recorded to assess activity in the soleus muscle (SOL) during the drop jump. Based on these jumps, the temporal occurrence of the peak of the SLR was determined in the rectified and averaged EMG. Peripheral nerve stimulation was timed so that the peak of the H-reflex coincided with either the instant of ground contact (GND) or the peak of the SLR (in line with Leukel et al., 2008a, 2008b). H-reflex excitability at GND was assessed as a reference to SLR. Stimulation at GND was triggered by means of a light barrier mounted 25 cm above the ground for the LH condition and 35 cm for the MH and HH conditions. Depending on the individual latencies of the H-reflex and the time between passing the barrier and touch down on a force plate (Kistler®, Winterthur, Switzerland), electrical stimulation was task-specifically triggered so that the H-reflex coincided with the moment of ground contact at each height (LH, MH, HH) (in line with Leukel et al., 2008a, 2008b). Subjects were instructed to rest for 2 min after every 20 jumps to avoid fatigue.

### EMG recording

Muscle activity was recorded from the SOL, the gastrocnemius medialis (GM), the rectus femoris (RF), and the tibialis anterior (TA) muscles of the right leg. Ag-AgCl bipolar surface electrodes (Hellige®, Freiburg, Germany, diameter 9 mm, center-to-center distance 3 cm) were filled with electrode jelly and attached to the skin over the muscle of interest in line with the presumed direction of the underlying muscle fibers. The reference electrode was placed on the tibial plateau. The position of the electrodes was marked with a waterproof felt pen and the markings were renewed in the training sessions from time to time. EMG signals were amplified ( $\times 1000$ ), bandpass-filtered (10–1000 Hz) and sampled at 4 kHz.

### Peripheral nerve stimulation

Rectangular current pulses lasting 1 ms were delivered to the posterior tibial nerve by a constant current stimulator (AS100 Alea Solutions®, Zurich, Switzerland). The anode, a  $10 \times 5$  cm dispersal pad, was fixed on the anterior aspect of the knee just below the patella. The cathode (2 cm in diameter) was placed in the popliteal fossa and moved stepwise until the best position for eliciting an H-reflex in the soleus muscle was found. It was ensured that electrical stimulation evoked no response in the TA muscle. The cathode was fixed with rigid tape. At the beginning of the experiment, H-reflex recruitment curves were recorded during normal stance. As the tibial nerve contains both, sensory and motor axons, electrical stimulation of this nerve elicits a reflectory response (H-reflex with a latency of approximately 35 ms) and a direct muscle response (M-wave; latency  $\sim 10$  ms) in the SOL. The H-reflex is mediated via Ia afferents to the  $\alpha$ -motoneuron and from there on to the neuromuscular junction. The M-wave travels from

the point of stimulation directly via motor axons to the neuromuscular junction. Low stimulation intensity results in a small H-reflex without any M-wave because the large diameter Ia afferents are recruited before the smaller motor axons. When stimulation intensity is successively increased from low levels sufficient to elicit a small H-reflex, up to  $H_{\max}$  and then  $M_{\max}$ , an H-reflex recruitment curve can be obtained (Zehr, 2002). Expressing the maximal H-reflex relative to  $M_{\max}$  ( $H_{\max}/M_{\max}$  ratio) solves the potential problem of ensuring identical EMG recording conditions in pre- and post-training (Aagaard et al., 2002). In the present study, SOL H-reflex recruitment curves were obtained during drop jumps at GND and at the time of the SLR at each height (LH, MH, HH).

### Kinematics

From each height, five jumps were recorded with a high-speed camera (100 frames per second) and analyzed afterwards using a commercially available video analysis system (Simi Motion®, Unterschleissheim, Germany). Anatomical landmarks (shoulder, hip, knee, and ankle center as well as the toe-cap) were marked to digitalize the subjects' movements and to obtain ankle, knee, and hip angles. The kinematic measurements were performed for SS1 and the control group by the high-speed camera and additionally by goniometers. The SSC2 group was measured in parallel and the joint angles in the SSC2 group were solely recorded using goniometers placed at the hip, the knee, and the ankle.

### Data analysis

Based on the H-reflex recruitment curves, maximum H-reflex ( $H_{\max}$ ) and maximum M-wave amplitudes ( $M_{\max}$ ) were determined.  $H_{\max}/M_{\max}$  ratios ( $H/M$  ratios) were calculated for each condition in the pre- and post-measurement and compared before and after training. Additionally,  $H/M$  ratios recorded during jumping were expressed as a percentage of the reference value obtained standing at rest (analogous to Voigt et al., 1998a).

Muscular activity during drop jump was analyzed in four time periods:  $t_1 = 100$  ms before ground contact to the duration of ground contact ( $-100$  to  $0$  ms; "pre-activation phase");  $t_2 = 20$ – $70$  ms after ground contact ("early reflex phase," which incorporated the SLR);  $t_3 = 70$ – $120$  ms ("late reflex phase" incorporating long latency reflexes); and  $t_4 = 120$ – $170$  ms ("push-off phase"). Root mean square values were determined for each phase of the drop jump. In the case of the SOL muscle, muscular activity was normalized to the  $M_{\max}$  obtained in the same muscle. The jumping height in trials testing maximum jump height was calculated by the formula: jump height =  $1/8 \times g \times t^2$ , where  $g$  is the acceleration due to gravity and  $t$  is the time of the flight phase. For evaluating drop jump performance, jump height as well as the duration of ground contact were considered to be of relevance. Thus, a performance index was calculated as the relationship between jump height and the duration of ground contact (performance index = height/time; Bruhn et al., 2004; Taube et al., 2007). Based on the kinematic data, the maximal countermovement (angular joint amplitudes) was determined for each subject and the corresponding angle joints of hip, knee, and ankle were compared before and after SSC training. Ankle joint stiffness was calculated for the eccentric phase of the drop jump according to Kubo et al. (2007). First, ankle joint torque (TQ) during the drop jump was estimated from the following equation (Kawakami et al., 2002; Kubo et al., 2007):

$$TQ = F_z L_1 \cos(A_j - 90)$$

where  $F_z$ ,  $L_1$ , and  $A_j$  are the vertical component of the ground reaction force, the length from the ankle joint to the ball of the foot, and the ankle joint angle, respectively. The ankle joint stiffness was calculated as the change in joint torque divided by the change in the ankle joint angle during the eccentric phase (Kuitunen et al., 2002).

### Statistics

To identify potential differences between groups in the pre-measurement, one-way ANOVAs were conducted for each parameter (rebound height, duration of ground contact, performance index, etc.). Changes in jumping height (rebound height), duration of ground contact, and the performance index were analyzed using a repeated measures ANOVA procedure with the within-subject factors time (pre- vs post-training measurement) and drop height (LH, MH, HH) and the between-subject factor group (SSC1, SSC2 and CON) [2 (time)  $\times$  3 (condition)  $\times$  3 (group)]. A repeated-measures ANOVA with the factors time (pre, post), drop height (LH, MH, HH), time of stimulation (ground vs SLR), and group (SSC1, SSC2, CON) [2 (time)  $\times$  3 (condition)  $\times$  2 (time of stimulation)  $\times$  3 (group)] was conducted to evaluate alterations in the  $H/M$  ratios. Changes in the normalized muscular activity of the SOL were analyzed by using a repeated-measures ANOVA with the factors time (pre, post), drop height (LH, MH, HH), phase ( $t_1, t_2, t_3, t_4$ ), and group (SSC1, SSC2, CON). Alterations in joint angles and ankle joint stiffness were analyzed with a repeated-measures ANOVA with the factors time (pre vs post), drop height (LH, MH, HH), group, and joint (hip, knee, ankle). In the case of significant  $F$ -values ( $P < 0.05$ ), the effects were separately analyzed for each group using repeated-measures ANOVAs to identify interaction effects. The differences between values at selected points in time or between conditions were compared by Bonferroni corrected paired two-sided tests (Student's  $t$ -test). To identify the differences in adaptations between the two training groups (SSC1 and SSC2), changes from pre- to post-measurement were expressed as percentage and Bonferroni-corrected unpaired two-sided tests were calculated. Correlations between changes in the  $H/M$  ratio with changes in ankle joint stiffness were determined using the Pearson's correlation coefficient. SPSS 16.0 software was used for statistical analysis. All values are presented as group mean values  $\pm$  standard deviation in the text, while the results in the figures are given as mean values  $\pm$  standard error of mean (SEM) for display reasons.

## Results

### Jump performance

#### Jump height and duration of ground contact

In the pre-measurement, neither the jump height nor the duration of ground contact differed significantly in any condition (LH, MH, HH) between groups (in all cases  $P > 0.1$ ). The jump performance was influenced by the drop jump training in two ways: first, the duration of ground contact was significantly altered (time<sub>pre/post</sub> group<sub>CON/SSC1/SSC2</sub>;  $F_{2,30} = 5.1$ ;  $P = 0.011$ ) and second, adaptations in jump height occurred (time<sub>pre/post</sub> group<sub>CON/SSC1/SSC2</sub>;  $F_{2,30} = 8.32$ ;  $P = 0.001$ ). The control group did not change any of those parameters in the post-measurement. However, subjects of SSC1 and SSC2 showed clear but different adaptations; after

SSC1, there was an interaction of time and duration of ground contact [ $F_{2,20} = 4.3$ ;  $P = 0.028$ ; Fig. 1(b)]. Although the time of ground contact was prolonged in each condition (LH, MH, HH), *post hoc* tests did not detect significant changes in any condition: LH ( $+12 \pm 16$  ms), MH ( $+14 \pm 23$  ms), and HH condition ( $+1 \pm 20$  ms; always  $P > 0.05$ ). On the contrary, subjects in the SSC2 group reduced their duration of ground contact [time<sub>pre/post</sub>;  $F_{1,10} = 9.0$ ;  $P = 0.001$ ; Fig. 1(b)]. *Post hoc* analysis revealed significantly decreased times of ground contact after SSC2 at LH ( $P = 0.002$ ) and HH ( $P = 0.028$ ), but only a trend at MH ( $P = 0.06$ ). The two training groups (SSC1 and SSC2) differed significantly with respect to their changes in duration of ground contact at LH ( $P = 0.004$ ) and MH ( $P = 0.012$ ) and showed a trend at HH ( $P = 0.06$ ).

Regarding the jump height, performance improved in the SSC1 training group to a comparable extent in each condition [time<sub>pre/post</sub>;  $F_{1,10} = 14.6$ ;  $P = 0.003$ ; *post hoc* tests: LH,  $P = 0.04$ ; MH,  $P = 0.003$ ; HH,  $P = 0.07$ ; Fig. 1(a)], but showed only a trend toward augmentation in the SSC2 group [time<sub>pre/post</sub>;  $F_{1,10} = 4.27$ ;  $P = 0.066$ ; *post hoc* tests were not significant for any drop height; Fig. 1(a)]. When comparing the adaptations of the two training groups, significant differences could be detected at LH ( $P = 0.03$ ) and MH ( $P = 0.03$ ).

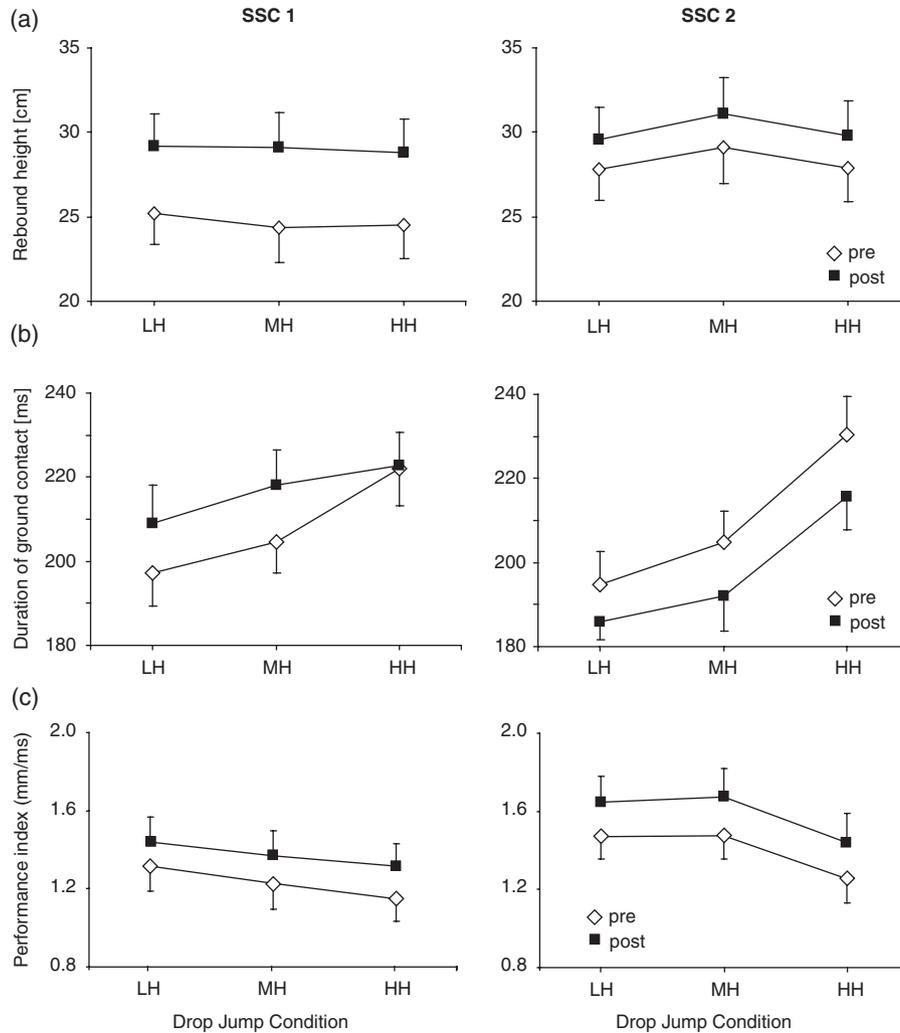
#### Performance index

There was a significant interaction of time and group [time<sub>pre/post</sub>  $\times$  group<sub>CON/SSC1/SSC2</sub>;  $F_{2,30} = 6.7$ ;  $P = 0.004$ ; Fig. 1(c)]. The values in the control group remained unaltered in the post-measurement ( $F_{1,10} = 0.6$ ;  $P = 0.44$ ). In contrast, the performance indices were significantly enhanced in the two training groups (SSC1:  $F_{1,10} = 9.5$ ;  $P = 0.012$ ; SSC2:  $F_{1,10} = 12.9$ ;  $P = 0.006$ ). Thereby, the improvements expressed as percentage of the initial values were almost identical for the two groups (SSC1 and SSC2) at all three drop heights (LH: SSC1 =  $+10 \pm 17\%$  vs SSC2 =  $+13 \pm 20\%$ ;  $P = 0.79$ ; MH: SSC1 =  $+13 \pm 17\%$  vs SSC2 =  $+14 \pm 13\%$ ;  $P = 0.92$ ; HH: SSC1 =  $+19 \pm 23\%$  vs SSC2 =  $+15 \pm 17\%$ ;  $P = 0.69$ ).

#### $H_{\max}/M_{\max}$ ratios

Pre- and post-measurements revealed no differences in the  $H/M$  ratios (time<sub>pre/post</sub>;  $F_{1,30} = 1.2$ ;  $P = 0.29$ ) in any group (time<sub>pre/post</sub>  $\times$  group<sub>CON/SSC1/SSC2</sub>;  $F_{2,30} = 1.4$ ;  $P = 0.26$ ) and at any stimulation point (time<sub>pre/post</sub>  $\times$  stimulation point<sub>GND/SLR</sub>;  $F_{1,30} = 0.5$ ;  $P = 0.49$ ). As reported in previous studies (Leukel et al., 2008a, 2008b),  $H/M$  ratios were dependent on the drop height condition (drop height<sub>LH,MH,HH</sub>;  $F_{2,60} = 4.9$ ;  $P = 0.011$ ). This was due to a great modulation of the H-reflex amplitude when record-

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**Fig. 1.** Drop jump rebound height (a), duration of ground contact (b), and performance index (c) before ( $\diamond$ ) and after ( $\blacksquare$ ) SSC1 and SSC2 training. (a) Subjects significantly increased their maximal rebound height from all three drop heights (LH = 30 cm; MH = 50 cm; HH = 75 cm) after SSC1. SSC2, on the other hand, caused only a trend toward augmented rebound heights. The duration of ground contact increased in the LH and MH but not the HH condition after SSC1 (b). In contrast, subjects reduced their duration of ground contact in all three jump conditions after SSC2. (c) The performance index was significantly enhanced after both SSC1 and SSC2. The improvements in performance index expressed as a percentage of the initial values were almost identical for the two training groups. SSC, stretch-shortening cycle; LH, low height; MH, medium height; HH, high height.

ings occurred at the time of the SLR (drop height<sub>LH,MH,HH</sub>;  $F_{2,60} = 7.2$ ;  $P = 0.002$ );  $H/M$  ratios were greatest when jumping from LH and smallest when jumping from HH (Fig. 2). No task-specific modulation was observed when the H-reflex coincided with the duration of ground contact (drop height<sub>LH,MH,HH</sub>;  $F_{2,60} = 0.7$ ;  $P = 0.50$ ). No changes in any group (CON, SSC1 and SSC2), condition (LH, MH, HH and stance) or stimulation time (GND and SLR) were apparent in the maximal M-waves from pre- to post-measurement (uncorrected Student's  $t$ -tests always  $P > 0.35$ ).

When the  $H/M$  ratios measured during activity were expressed as a percentage of the  $H/M$  ratios assessed at rest (standing) before and after SSC

training, there were still no effects [method proposed in Voigt et al. (1998a); results not illustrated].

### Muscular activity

Normalization to  $M_{\max}$  of the muscular activity of the SOL muscle revealed a training-related change in activity, which was specific to the training group and the phase of the movement ( $\text{time}_{\text{pre/post}} \times \text{phase}_{1-14} \times \text{group}_{\text{CON/SSC1/SSC2}}$ ;  $F_{6,180} = 4.1$ ;  $P = 0.001$ ; Fig. 3). Following SSC1 training, muscular activity of the SOL did not change in the early phase of the drop jump (pre-activation and early reflex phase:  $-100$  to  $+70$  ms; 0 ms corresponds to the instant of ground contact). In contrast, muscular activity during

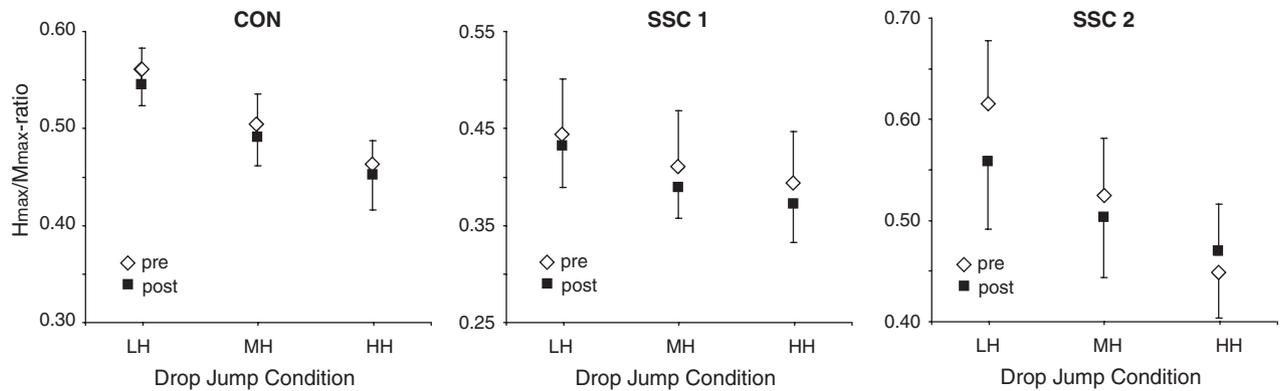


Fig. 2.  $H_{\max}/M_{\max}$  ratios of the control (CON), the SSC1 and SSC2 group at jumps from different drop heights [low height (30 cm) = LH; moderate height (50 cm) = MH; and high height (75 cm) = HH]. Before training (◇), all three groups demonstrated a significant drop-height-specific H-reflex modulation. In the post-measurement (■), the same results were obtained except for the SSC2 group, which did not show a significant drop-height-dependent H-reflex modulation any more. SSC, stretch-shortening cycle; LH, low height; MH, medium height; HH, high height.

the late phase of ground contact (70–170 ms) increased ( $\text{time}_{\text{pre/post}} \times \text{phase}_{t1-t4}$ ;  $F_{3,30} = 5.0$ ;  $P = 0.007$ ; Fig. 3). Following SSC2 training, the muscular activity did not change during the late phase of ground contact but in the early reflex phase ( $\text{time}_{\text{pre/post}} \times \text{phase}_{t1-t4}$ ;  $F_{3,30} = 5.1$ ;  $P = 0.006$ ; Fig. 3).

Figure 4 illustrates one participant's data before and after SSC1 training and pre- and post-measurement data of one subject from the SSC2 group. It can clearly be seen that muscular adaptations occurred at different times with regard to the training intervention; after SSC1, muscular activity increased toward push-off while SSC2 resulted in an increased muscular activity at the time of the SLR. These neuromuscular adaptations probably influenced the pattern of the ground reaction forces; after SSC1, a prolonged time of ground contact was apparent whereas the opposite was true for SSC2 (Fig. 4).

In the SSC1 group, the RF muscle behaved similar to the SOL, showing unchanged activity in the early phase of drop jump and increased neural drive in the later part of ground contact ( $\text{time}_{\text{pre/post}} \times \text{phase}_{t1-t4}$ ;  $F_{3,30} = 4.7$ ;  $P = 0.008$ ). In the SSC2 group, the activity of the RF was not altered after training. No training-induced changes at all were seen in the GM and the TA as well as in all muscles tested in the control group (not illustrated; all statistical values above  $P = 0.23$ ).

### Motion analysis

Unfortunately, the signals of the goniometers used in the SSC2 could not be analyzed. Although the signals looked well online, later analysis revealed measurement errors, which were caused by a loose contact within the cable connecting the goniometer to the A/D converter. Thus, the kinematic data are missing for the SSC2 group.

Even though the kinematic data are solely available for the control and SSC1 group, it is nonetheless illustrated as it may provide important additional information due to the following two reasons: first, the longitudinal data of the SSC1 group can be better compared with other SSC-training studies focusing on changes in lower leg stiffness rather than the neuromuscular activity (Hunter & Marshall, 2002; Kubo et al., 2007). Second, the cross-sectional data obtained in the pre-measurement highlight the previously proposed relationship between H-reflex excitability and lower leg stiffness (Dietz et al., 1979; Dyhre-Poulsen et al., 1991; Gollhofer et al., 1992; Voigt et al., 1998b; Komi, 2003; Hobara et al., 2007).

### Kinematics

SSC1 training significantly increased maximal joint flexion during the eccentric phase of the drop jump (countermovement), whereas there were no changes in the CON group ( $\text{time} \times \text{group}$  effect;  $F_{1,18} = 8.77$ ,  $P = 0.008$ ). In the training group, alterations in the depth of countermovement were most pronounced for the ankle and knee joint and only minor for the hip ( $\text{time}_{\text{pre/post}} \times \text{joint}$ ;  $F_{2-12} = 8.9$ ;  $P < 0.004$ ; Fig. 5). Most interestingly, training-induced changes occurred solely in jumps from the lower drop heights, i.e., from 30 and 50 cm, but not from 75 cm (condition:  $F_{2-12} = 37.4$ ;  $P < 0.001$ ; Fig. 5).

### Joint stiffness

Ankle joint stiffness did not change after SSC1 training ( $\text{time} \times \text{group}$  effect;  $F_{1,18} = 0.00$ ;  $P = 0.99$ ). However, in pre- and post-measurement, drop height was shown to have a major impact on ankle joint stiffness resulting in reduced stiffness when jumping from greater heights (drop height<sub>LH,MH,HH</sub>;  $F_{2,34} = 20.78$ ;  $P < 0.001$ ).

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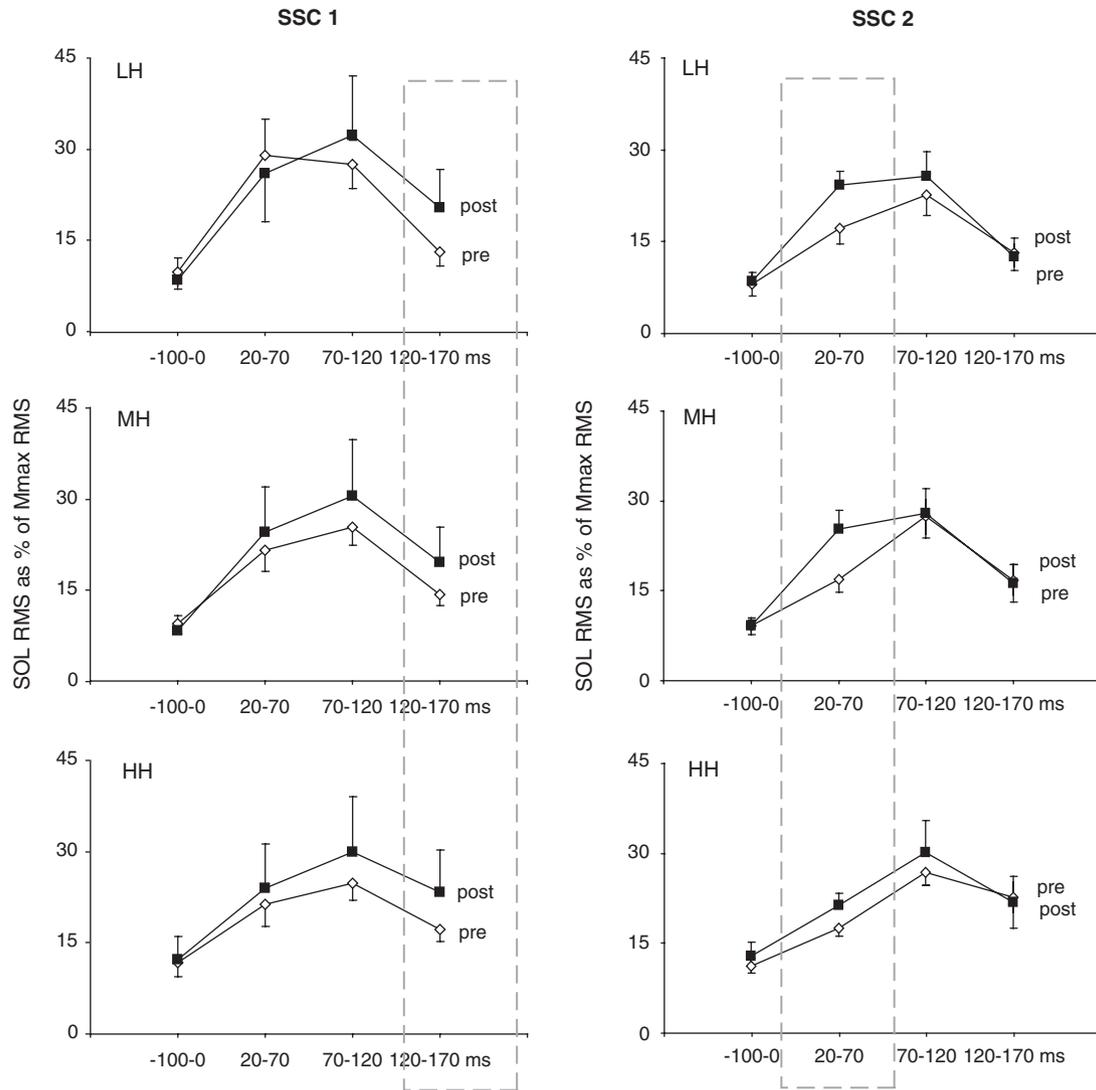


Fig. 3. Muscular activity of the M. soleus during drop jumps from 30 cm (LH), 50 cm (MH) and 75 cm (HH) in pre-measurement ( $\diamond$ ) and post-measurement ( $\blacksquare$ ) of SSC1- and SSC2-trained subjects. After SSC1, muscular activity remained unchanged in the pre-activation phase ( $-100$  to  $0$  ms before touch down) and the early duration of ground contact ( $20$ – $70$  ms = “early reflex phase”). In later phases of ground contact ( $70$ – $120$  and  $120$ – $170$  ms) muscular activity increased following SSC1 training. In contrast, changes after SSC2 were most pronounced shortly after ground contact in the “early reflex phase” but displayed no significant changes in any other phase. SSC, stretch-shortening cycle; LH, low height; MH, medium height; HH, high height.

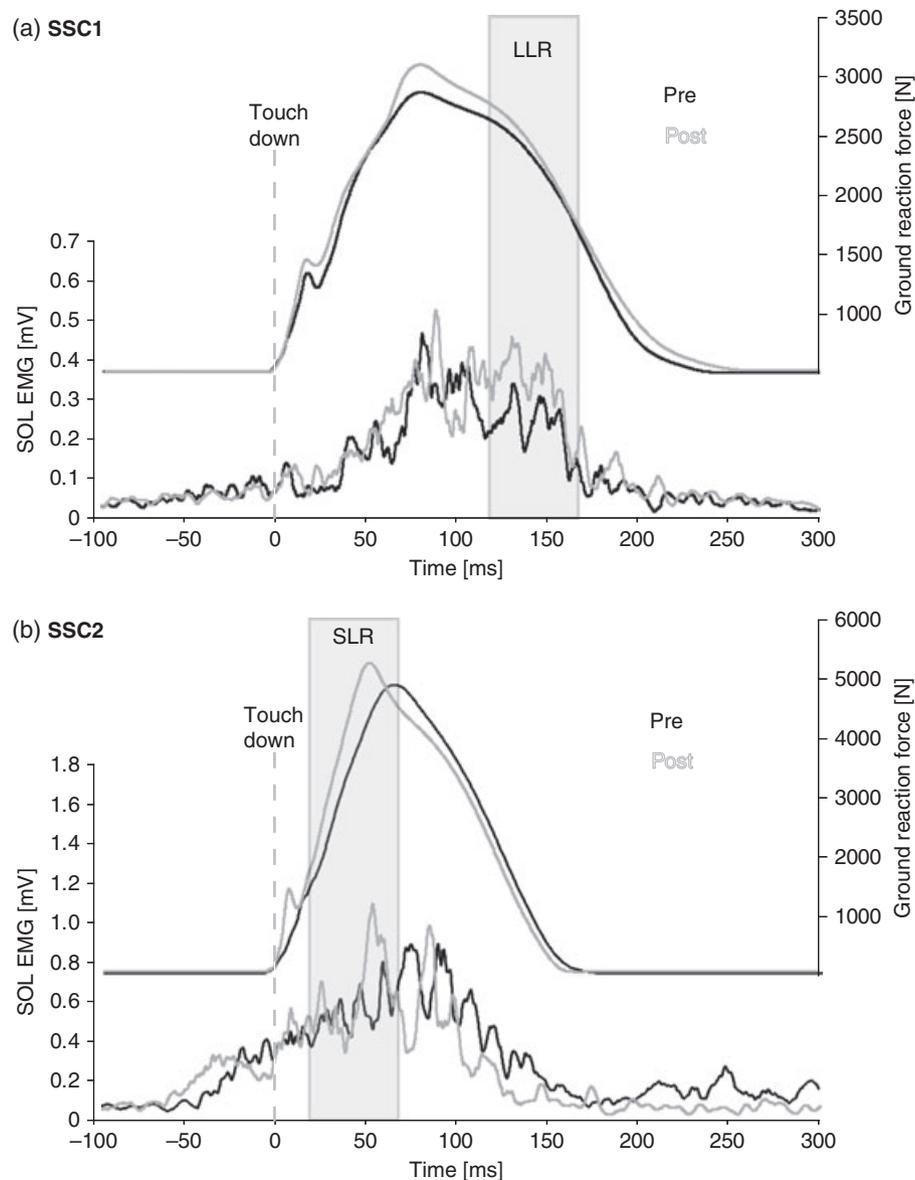
### Correlation between ankle joint stiffness and $H/M$ ratios from different drop heights

Data assessed in the pre-measurement revealed that the changes in ankle joint stiffness due to increases in drop height (from LH to MH and from LH to HH) were positively correlated with changes in the  $H/M$  ratio (Fig. 6). This means that subjects who reduced their ankle joint stiffness largely when jumping from MH instead of LH concomitantly demonstrated great reductions in their  $H/M$  ratios [ $r = 0.66$ ;  $P = 0.003$ ; Fig. 6(a)]. Similar results were obtained when changes in ankle stiffness and  $H/M$  ratios were correlated when switching from LH to HH [ $r = 0.56$ ;

$P = 0.015$ ; Fig. 6(b)]. The post-measurement data partially confirmed this observation resulting in a significant correlation between changes in ankle joint stiffness and changes of  $H/M$  ratios when switching from LH to MH ( $r = 0.50$ ;  $P = 0.036$ ) but not from MH to HH ( $r = 0.22$ ;  $P = 0.37$ ; post-measurement data are not displayed).

### Discussion

It was hypothesized that the changes in neuromuscular activity and jumping technique in response to SCC training are specifically linked to the applied



*Fig. 4.* Muscular activity of the M. soleus during drop jumps from 30 cm of one SSC1-trained subject (a) and one SSC2-trained subject (b). After SSC1, muscular activity remained unchanged in the pre-activation phase but was enhanced in later phases of ground contact (120–170 ms; gray-shaded box). At the same time, the duration of ground contact was prolonged (a). In contrast, electromyogram changes after SSC2 were most pronounced shortly after ground contact in the “early reflex phase” (20–70 ms; gray-shaded box) but displayed no significant changes in any other phase (b). The duration of ground contact was reduced after SSC2. LLR, long latency response; SLR, short latency response; SSC, stretch-shortening cycle.

drop heights. In particular, changes in the muscular activity and H-reflex excitability at the time of the SLR together with alterations in performance-related biomechanical parameters of the drop jumps were expected to be determined by the applied stretch loads during the training interventions. The results of the present study confirm our initial hypotheses.

#### Training-specific adaptations after SSC1

After SSC1 training, there were neither changes in the muscular activity of SOL and GM nor in the antagonist TA or the H-reflex at the time of the SLR.

Therefore, the enhanced rebound heights following SSC1 training cannot be explained by alterations of the early stretch reflex component in all likelihood. Also, the increased jump height cannot be attributed to an enhanced ankle joint stiffness in the eccentric phase, as this parameter remained unchanged after SSC1 training. This result seems reasonable as the spinal H-reflex activity and the ankle joint stiffness were significantly correlated for the jumps from different drop heights (Fig. 6). As reported previously (Leukel et al., 2008a, 2008b) and confirmed in the present study, the H-reflex excitability was decreased with increasing drop heights. At the same

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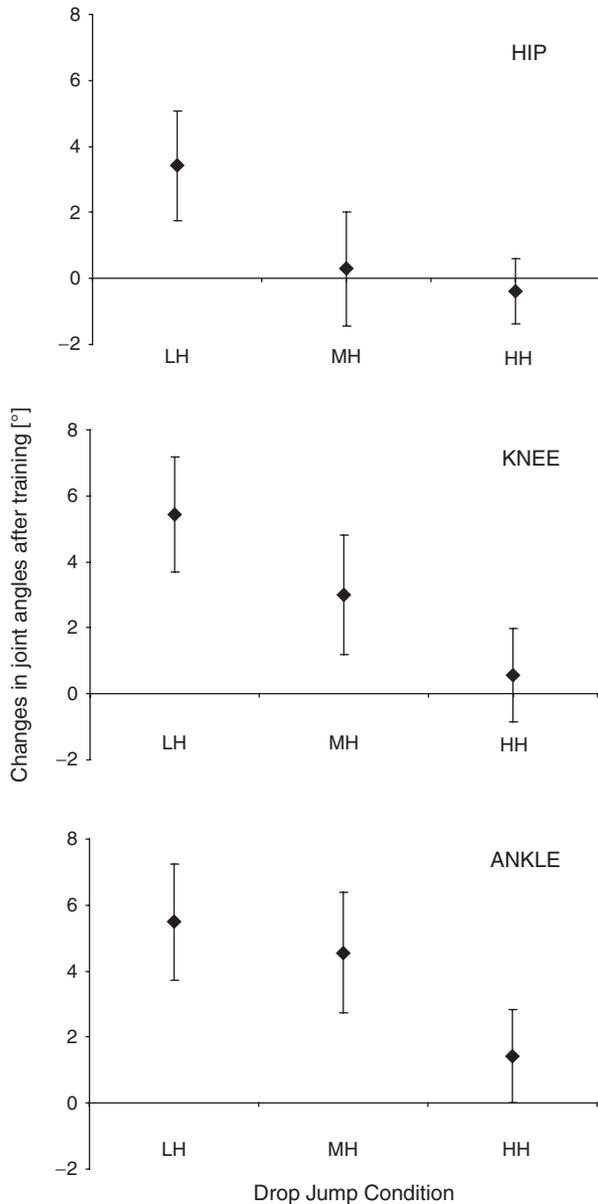


Fig. 5. Changes in joint angles (hip, knee, and ankle angles) during drop jumps from 30 cm (LH), 50 cm (MH), and 75 cm (HH) after SSC1 training. Subjects demonstrated greater hip, knee, and ankle flexion after training when tested in the LH condition. Knee and ankle angles also decreased in the MH condition. No changes occurred in the HH condition. Positive values indicate greater joint flexion. SSC, stretch-shortening cycle; LH, low height; MH, medium height; HH, high height.

time, the ankle joint stiffness was reduced. This correlation may strengthen the long-held assumption (Dietz et al., 1979; Dyhre-Poulsen et al., 1991; Gollhofer et al., 1992; Voigt et al., 1998b; Komi, 2003; Hobara et al., 2007) that spinal reflexes at the time of the SLR affect the ankle joint stiffness during SSC movements.

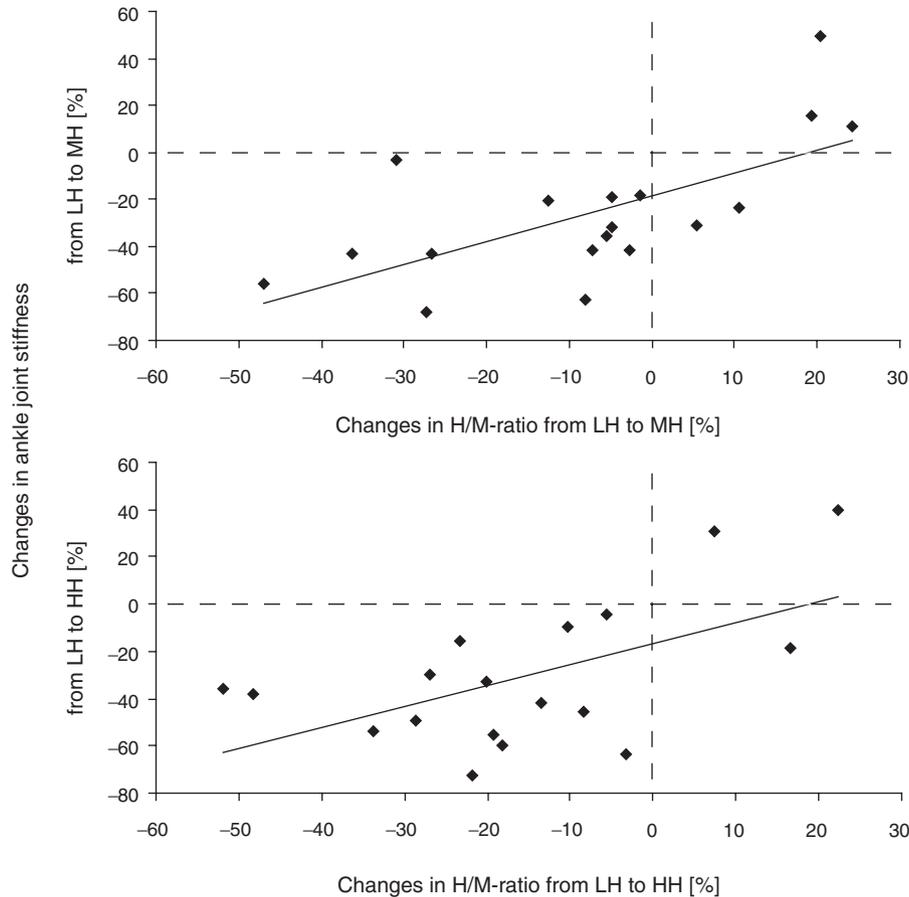
Although SSC1-trained subjects did not alter their ankle joint stiffness, they significantly increased their countermovement, i.e., they made use of greater

ankle and knee flexion in the eccentric phase of the drop jump. As subjects displayed an unaltered EMG activity in agonists and antagonists in this early period after ground contact but a greater joint flexion, SSC1 training may have changed the EMG to torque relationship. It might be speculated that the extensive eccentric loads in jumps from HH could have led to adaptations within the muscle and/or tendon. For instance, evidence from animal studies suggests that eccentric resistance training increases muscle fascicle length by increasing the number of sarcomeres in series (Morgan & Allen, 1999; Butterfield & Herzog, 2006). Exercise-induced changes in muscle fascicle length were also demonstrated in humans (Reeves et al., 2005, 2009; Blazevich et al., 2007) and could therefore explain the altered torque-angle relationship in the present study. With the present methodology, this issue cannot be answered but it has to be underlined that the present training was restricted to 4 weeks in order to induce predominantly neural rather than tendo-muscular adaptations (Moritani & deVries, 1979).

Apart from the greater countermovement, subjects also demonstrated significant increases in the ground contact time when jumping from LH and MH after training. However, most relevant with respect to improved jump performance may be the observation of increased muscular activity in the soleus and RF muscles in the late phase of the drop jump. This increased muscular activity shortly before take-off combined with the longer distance (greater depth of countermovement) and time for acceleration (ground contact time) probably enabled subjects to increase their take-off velocity.

### Adaptations after SSC2 training

The SSC2 training resembled the SSC1 training but incorporated only LH drop heights (30 cm). We hypothesized that the SSC2 training should exert a stronger influence on the neuromuscular activity at the time of the SLR because subjects would not have to apply similar strong inhibitory mechanisms in the eccentric phase than during jumps from high drop heights. The normalized activity of the SOL muscle was indeed enhanced at the time of the SLR. However, the  $H/M$  ratios were not augmented. Thus, it might be argued that a more efficient (e.g. removal of inhibition) Ia afferent transmission to the  $\alpha$ -motoneurons was not responsible for the increased muscular activity. Alternatively, the increase of the normalized soleus background EMG might be caused by enhanced supraspinal contributions. Previously, we demonstrated that during hopping the muscular activity at the time of the SLR (“early reflex phase”) is not only exclusively generated by stretch reflex responses but also depends on the



*Fig. 6.* Correlation of drop-height-dependent changes in the ankle joint stiffness and changes in the  $H/M$  ratios. (a) Subjects of SSC1 and CON demonstrated a correlation when comparing ankle joint stiffness and  $H/M$  ratios in the LH and MH conditions ( $r = 0.66$ ;  $P = 0.003$ ) as well as when comparing ankle joint stiffness and  $H/M$  ratios in the LH and HH conditions ( $r = 0.56$ ;  $P = 0.015$ ) (b). SSC, stretch-shortening cycle; LH, low height; MH, medium height; HH, high height.

contribution of cortical centers (Zuur et al., 2010). With the methods used in the present study, the site and the mechanism(s) of adaptation leading to an enhanced neural drive cannot be identified. However, irrespective of the exact mechanism(s), it is very likely that this augmented neural drive at the SLR enabled the subjects to reduce their times of ground contact and to augment their performance indices. This strategy, however, does not seem beneficial in increasing the rebound height, as there was only a trend toward augmentation.

#### “Movement instruction” vs “constraints of the motor task”

In all training and testing sessions, the subjects were instructed to “rebound as fast and as high as possible,” i.e., to reduce the duration of ground contact and to enhance the jump height. However, subjects of the SSC1 group enhanced their rebound height but displayed prolonged times of ground contact. In contrast, SSC2-trained subjects reduced the duration of ground contact but showed non-significant changes in the rebound height. Apparently, no group

put the movement instructions completely into action. Previously, Hunter and Marshall (2002) presumed that if subjects were not advised by instructions like: “Keep the duration of ground contact as short as possible,” or “Bend your knees very little,” subjects would automatically adapt their jumping strategy in the direction of a lower leg stiffness, greater depth of countermovement, and longer ground contact times. This assumption resulted from the observation that non-instructed subjects adopted such a strategy after 10 weeks of drop jump training from different drop heights (30, 45, 60, 75, and 90 cm). However, other studies could not confirm this hypothesis. For instance, Kubo et al. (2007) did not instruct their subjects to rebound as fast as possible but observed enhanced lower leg stiffness without changes in the angular velocities. On the first view, the outcome after drop jump training seems therefore arbitrary. However, when considering the drop heights applied during training, it becomes obvious that the two interventions [SSC1 and Hunter & Marshall (2002)] incorporating high drop heights (above 75 cm) led to greater depth of the

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countermovement, longer duration of ground contact and unchanged or decreased lower leg stiffness. In contrast, training from lower drop heights (under 60 cm) resulted in enhanced lower leg stiffness (Kubo et al., 2007), decreased countermovement, and shorter duration of ground contact [SSC2 and Bubeck et al. (2003); de Villarreal et al. (2008)]. These observations show the importance of the drop height applied during the training. Consequently, it can be concluded that, at least in some cases, the direction of adaptation is not guided mainly by the instruction but by the task itself. This was most evident in the SSC1 group in which the jumping technique in the LH and MH conditions was altered in direction of the HH condition, whereas alterations in the HH condition were minor or non-existent. Therefore, we can speculate that the jumping strategy used in the HH condition was transferred to the lower height conditions. The reason for the strong influence of the HH condition on the jump technique may lie in the responsibility of the neuromuscular system to avoid overload injuries. Kjaer (2004) reported the maximal loading for several tendons and demonstrated that the Achilles and patella tendons work in ranges relatively close to their point of failure. Especially when jumping, very high forces are exerted on the tendons (Fukushiro et al., 1995; Kjaer et al., 2005). Thus, neural control may adapt to high drop heights in terms of a reduced spinal excitability to reduce the stiffness of the muscle–tendon complex and avoid the occurrence of overload injuries (Kyrolainen & Komi, 1995; Komi & Gollhofer, 1997; Komi, 2003; Leukel et al., 2008b). Interestingly, elderly people apply the “high drop height technique” already in jumps from low heights. Compared with young subjects, they showed less muscular activity during the pre-activation and early breaking phase (eccentric phase = “early reflex phase”) of drop jumps but increased activity in the push-off phase (Hoffren et al., 2007). This technique resulted in a lower stress of the tendo-muscular system in the eccentric phase. In young subjects, training incorporating high drop heights (SSC1) may transfer such a “prevention strategy” to other jump conditions (LH, MH) despite the instruction to rebound as fast as possible. The discovery of a task-dependent “overruling” of the movement instruction is important for subsequent plyometric training interventions. It is not only sufficient to ask the subjects to perform a certain technique (e.g. realization of short ground contact times) but also to provide the optimal loading (drop height).

### Functional considerations

The present longitudinal study demonstrated a clear relationship between the stretch load (drop height) and the resulting adaptations in neuromuscular ac-

tivity and performance. Previous cross-sectional studies proposed that in order to maximize the mechanical output of knee extensors and plantar flexors during drop jump training, athletes should utilize a “bounce drop jump technique,” i.e., to reverse the downward velocity into an upward one as soon as possible after landing (Bobbert et al., 1987a). This “recommendation” was founded on the essential need for effective storage of elastic energy in the transition from the eccentric to the concentric phase (Kyrolainen & Komi, 1995; Komi, 2003). Regarding the drop height, it was suggested to train from low drop heights (20–40 cm) to avoid a sharp heel impact in the eccentric phase (Bobbert et al., 1987b; Lees & Fahmi, 1994). The SSC2 training in the present study resembled such a training and caused enhanced neuromuscular activity at the time of the SLR, which probably enabled subjects to reduce their times of ground contact but proved ineffective in increasing the rebound height. Conversely, SSC1-trained subjects enhanced neuromuscular activity toward the push-off, which not only led to improved vertical rebound heights but also prolonged times of ground contact. In line with Hunter and Marshall (2002), the incorporation of high drop heights led to a greater depth of the countermovement. Thus, SSC1 and SSC2 caused distinct neuromuscular and biomechanical adaptations, which were dependent on the training regime, or more specifically, the drop height (or stretch load). To compare the efficiency of the two training regimes, the training-related changes in performance were analyzed. For this purpose, the workload was time-normalized, i.e., the rebound height was divided by the duration of ground contact and expressed as the performance index (performance index = rebound height/contact time  $\times$  s/m; Bruhn et al., 2004; Taube et al., 2007). This analysis revealed that both SSC interventions led to significant and – most interestingly – comparable improvements. As the gain in performance was not different after SSC1 and SSC2, it might be speculated that the training outcomes are limited by the amount of reactive performance the tendo-muscular system can execute. The decision whether to apply SSC1 or SSC2 should therefore strongly depend on the specific demands of the particular sports discipline. High drop heights should be implemented into the training regime if the goal is to maximize the rebound height and if the duration of ground contact is not a limiting factor of performance. On the other hand, low drop heights should be preferred to maximize power output in time critical disciplines. This drop-height-dependent specificity of the neuromuscular adaptations may therefore also partly explain the great variations in training efficiency of SSC interventions reported in a recent meta-analytical review (Markovic, 2007).

## Perspectives

The present study is the first one to highlight the fact that differences in the drop height applied during SSC training determines the neuromuscular adaptations. As the neuronal control in turn seems to strongly affect the performance-related parameters, this finding may be of great relevance not only to understand the task specificity of neural adaptations in SSC movements but

may also help to conceptualize appropriate training regimes.

**Key words:** H-reflex, drop jump, peripheral nerve stimulation, plyometric training.

## Acknowledgement

This project was funded by the Bundesinstitut für Sportwissenschaft (BISp; Germany) and by the Bundesamt für Sport (BASPO; Switzerland).

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