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Four weeks of training in a sledge jump system improved the jump pattern to almost natural reactive jumps

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Abstract In spite of extensive training regimens during long-term space missions with existing training devices, astronauts suffer from muscle and bone loss. It has been suggested that reactive jumps inducing high forces in the muscles—consequently exposing the bones to high strains—help to counteract these degradations. In a previous study, a new sledge jump system (SJS) was found to allow fairly natural reactive jumps. The aim of the present study was to evaluate if training in the SJS would further reduce the differences between jumps in the SJS and normal jumps, particularly with respect to ground reaction forces (GRF) and rate of force development (RFD). Sixteen participants in a training group (TG) and 16 in a control group (CON) were tested before and after the TGs four-week hopping training in the SJS. During the tests, kinetic, kinematic and electromyographic data were compared between hops on the ground and in the SJS. After the training period, the GRF, the RFD and the leg stiffness in the SJS significantly increased for the TG (but not for CON) by 10, 35 and 38%, respectively. The kinematic and electromyographic data showed no significant changes. A short training regimen in the SJS reduced the differences between jumps in the SJS and normal jumps. Considering that a natural movement that exposes the muscles and thus also the bones to high loads is regarded as important for the preservation of muscle and bone, the SJS seems to be a promising countermeasure.

Keywords Space · Astronauts · SSC · Countermeasure

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Introduction

In spite of extensive training regimens before and during long-term space missions with existing devices such as treadmills, cycle ergometers or a weight-lifting device (advanced resistive exercise device, ARED), astronauts still suffer from muscle and bone loss, at least partly caused by the absence of high forces acting on the muscles and therefore also the bones (Ohshima 2010a). This loss is most pronounced in the leg muscles (particularly, the leg extensor muscles) and bones, as the legs bear most of the weight under normal gravity conditions and consequently the load difference between normal and space conditions is much higher than for the arms or the trunk. Recently, it has been shown in bed rest studies that even relatively short periods (8 weeks) of bed rest can result in a shank muscle loss of about 30% and a bone loss of about 4% (Armbrecht et al. 2010; Belavý et al. 2009; Rittweger et al. 2010). The data available from long-term space missions indicate that the average bone mineral loss in weight-bearing bones during space flight is about 1–2% per month (Ohshima 2010b). The resulting loss of bone strength (i.e., the bone's capability to withstand high forces) is probably even higher, as measurements of bone mass (either measuring bone mineral content or bone mineral density) provide no information about bone geometry, which is also an important factor for bone strength (Keyak et al. 2009).

The forces that are necessary for the deformation of the bone are mainly provided by the muscles that are attached to the bone (Frost and Schönau 2000; Rittweger et al. 2000). On earth, physical activities involving walking, running or jumping induce sufficient muscle activity to generate those forces. In microgravity, muscular activity is heavily reduced, which leads to a loss of muscle mass and a reduction of the muscles' capability to quickly produce high forces, probably caused by similar disuse-induced mechanisms as on earth (Al-Shanti and Stewart 2009; Fitts et al. 2001; Lang et al. 2010). The exact mechanisms of bone loss are not very clear yet, but for astronauts the main cause seems to be the lack of bone deformation as a consequence of the lacking gravitational loading and low muscular forces. Consequently, exercise is likely to be an important factor in the gain or retention of bone mass and strength, as indicated for example by the unilateral bone hypertrophy of professional tennis players (Jones et al. 1977; Suominen 1993). A model that is commonly used for the explanation of bone loss and formation is the mechanostat model introduced by Frost (Frost 1987). It states that bones adapt their strength to the mechanical loads they are exposed to (primarily generated by the attached muscles), either by a decrease or increase of bone mass or a change in geometry. If the strain (i.e., the ratio of elongation with respect to the original length) lies within a range of normal use (about 1,000–2,000 microstrains), the bone retains its strength. If the strain is lower, degradation of bone material takes place; if it is higher, new bone is formed or the trabecular bone is rearranged (i.e., the bone geometry is changed). It has also been proposed that the strain rate (i.e., the velocity at which the bone is deformed) might be important as a bone formation stimulus (Turner et al. 1995). Thus, to increase bone strength (or at least retain the bone strength in special situations, such as long-term space missions), high forces acting on the bone in short time periods resulting in a high rate of force development (RFD) are necessary to generate high strains and high strain rates (Suominen 1993).

A natural movement that generates high forces as well as high rates of force development is a reactive jump, characterized by short ground contact times (GCT) and a high leg stiffness that allows the storage of energy in the eccentric phase of the jump and its release in the subsequent concentric phase (Asmussen and Bonde-Petersen 1974; Gollhofer and Kyröläinen 1991). Reactive jumps have been identified as having the highest peak ground reaction forces (GRF) and RFD among the tested exercise modes (Ebben et al. 2010), generating peak GRF of about seven times the body weight. Since reactive jumps are usually performed without heel contact, those high GRF induce at least equally high forces in the involved leg muscles, which are in turn transferred to the bones. Therefore, the authors of the study concluded that reactive jumps had the greatest potential as an osteogenic stimulus (Ebben et al. 2010). In addition to exposing the tendo-muscular system to high loads, reactive jumps also challenge the neuromuscular system, as they represent a highly dynamic movement that requires a well-timed activation and coordination of the muscles, as well as the integration of a number of sensory inputs, such as muscle spindles, Golgi tendon organs or visual and vestibular feedback (Dietz 1992; Gollhofer 1987; Gollhofer and Kyröläinen 1991). This high demand on the motor control during a fast, natural movement might be helpful against the deleterious effects of prolonged spaceflights on the sensorimotor system (Clément et al. 2005), making reactive jumps a candidate for an integrated countermeasure for muscle loss, bone loss and degradations of the the sensorimotor system.

To use reactive jumps as a countermeasure in weightlessness, the lack of a gravitational force has to be compensated for. The sledge jump system (SJS) employed in this study (developed by Novotec Medical on behalf of the European Space Agency) uses low-pressure cylinders to generate forces that can be matched to the trainee's bodyweight, thus mimicking the force of gravity. A previous study already focused on the question whether jumps in this SJS would be comparable to natural jumps on the ground (Kramer et al. 2010). In some parameters (ankle and knee angles, range of motion), there were no differences between the sledge jumps and the normal jumps, and other parameters showed differences of approximately 25% (peak force, RFD, GCT, leg stiffness, muscle preactivity). This means that subjects not familiar with the system were already able to perform quite natural jumps in the SJS. While this is a very good basis, it would be beneficial for the use of the SJS as a countermeasure to bring the jump pattern in the SJS even closer to the one of natural jumps, particularly the GRF, RFD, leg stiffness and GCT.

Therefore, the aim of the present study was to evaluate if a 4-week training in the SJS would reduce the differences observed in the cross-sectional study between normal jumps on the ground and jumps in the SJS, and in particular improve the SJS jump pattern toward higher peak forces, higher RFD, higher leg stiffness and shorter GCT.

Methods

Subjects

Thirty-two healthy subjects volunteered to participate in this study. The participants were physically fit students at the department of sports science, were not involved in any other systematic training during the experiment and had not used the SJS before. Before taking part in the study, all participants gave written informed consent to the experimental procedure, which was approved by the ethics committee of the University of Freiburg and in accordance with the latest revision of the Declaration of Helsinki. All participants were healthy with no previous neurological irregularities or injuries of the lower extremity. They were randomly assigned to the training group (TG, 6 female and 10 male participants, age 23 ± 2 years, height 175 ± 7 cm and weight 70 ± 9 kg) or the control group (CON, 8 female and 8 male participants, age 23 ± 2 years, height 175 ± 10 cm and body mass 69 ± 12 kg).

Sledge jump system

The SJS (see Fig. 1) was developed by Novotec Medical GmbH (Pforzheim, Germany). It consists of a tilting table and a lightweight sledge (5 kg) that is attached to a rail on both sides of the table. The tilt angle of the table is continuously variable between zero (horizontal position, used in this study) and 90° (vertical position). The construction allows the sledge only to slide alongside the rails, i.e., when the table is in a horizontal position, the sledge can slide only in a horizontal direction. Note though that the sledge is attached to the rails with straps that allow some movement perpendicular to the movement direction as well as some rotation (see Fig. 2). The participant is attached to the sledge via four straps, two around the thighs and two around the shoulders, allowing him to move in a natural manner (see Fig. 1). The force that pulls the sledge toward the force plates is generated by two low-pressure cylinders. One cylinder can generate 500 N at full capacity, i.e., any force between zero and 1,000 N can be set by altering the pressure of the cylinders. In this study, the pressure was adjusted in a way that the forces produced by the cylinders matched the subject's weight. The SJS was used in the horizontal position because that way, no gravitational forces act in the direction of the jump, only the forces generated by the cylinders.

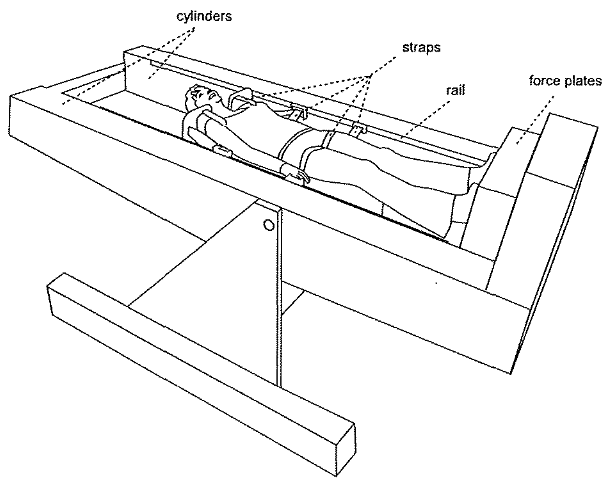

Fig. 1 The sledge jump system in the horizontal position. The participant is fixed to the wooden sledge with straps. The straps are attached to the rails and can slide in the direction of the rails with minimal friction. The participant stands on two force plates (separated, one for each foot). Reprinted from (Kramer et al. 2010), with permission from Elsevier

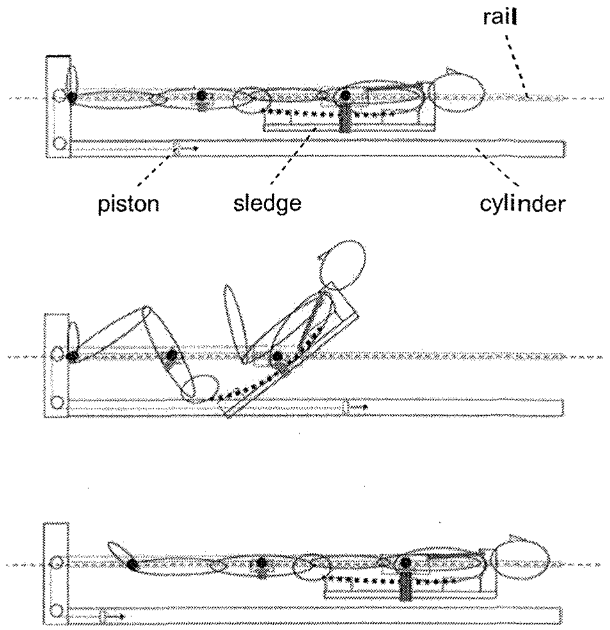

Fig. 2 A longitudinal section of the SJS. The two low-pressure cylinders pull the participant onto the force plates. The *second drawing* illustrates the freedom of movement in the ankle, knee and hip joint (the downward movement of the hip is not constrained by the cylinders like the drawing might suggest, as the cylinders are to the left and right of the participant, and not below; see Fig. 1). Note that the figure is not intended to show a hopping. Reprinted from (Kramer et al. 2010), with permission from Elsevier

Experimental design

To test the effects of a 4-week training regimen in the SJS, all subjects were tested before and after the training period. Sledge hops (SH) on both legs before the training period were compared to the SH after the training period. In addition, normal hops (NH) on the ground on both legs were included in the tests before and after the training period to assess the specificity of the training adaptations. Prior to the first test, all participants were shown and practiced the correct execution of the hops on the ground: the upper body was kept upright and the arms had to be kept crossed in front of the chest throughout the jumps. After a 10-min warm-up phase (consisting of running, tapping and hopping), the hops were performed with the instruction to jump as stiff as possible, i.e., to keep the contact time as short as possible, insuring more consistent and thus more comparable jumps. One trial consisted of 60 hops with a 2-min break after every 20 hops to avoid fatigue. Between the 60 SH and the 60 NH, the subjects were given as much time to recover as they deemed necessary. The jumps were performed bare-footed on two force plates (AMTI®, Watertown, USA with a sampling frequency of 1,000 Hz for the normal jumps; in the SJS, two Leonardo® platforms by Novotec Medical GmbH, Pforzheim, Germany with a sampling frequency of 800 Hz were used). The GRF perpendicular to the force plates were recorded separately for the right and the left foot and synchronized to the EMG signals.

Training

The TG trained over a period of 4 weeks, with a total of 12 training sessions. All sessions were documented, surveyed and supervised by the authors of the study. The CON did not train at all. The participants of both groups were instructed to maintain their normal level of physical activity during the experimental period. One training session consisted of five series of 20 hops each in the SJS with 2 min of recovery time in between series. The instruction for the participants was as follows: "Jump as stiff as possible, i.e., flex the ankle, knee and hip joint as little as possible while still jumping as high as the high stiffness allows. Jump as constant as possible". This instruction was repeated and the correct execution demonstrated by the authors whenever necessary.

Kinematics

The hops were recorded with a marker-based motion capturing system (Vicon, Oxford, UK) using 12 cameras (MX40, 200 Hz). The markers were placed on the following anatomical landmarks of the right leg: hallux, fifth metatarsal bone, lateral malleolus, lateral knee joint center and greater trochanter. In addition, one marker was placed on the sternum. Those markers were used to generate a 2D model of the right leg, from which three joint angles were calculated: the ankle angle as the angle between the vectors malleolus-metatarsal and malleolus-knee, the knee angle from the vectors knee-trochanter and knee-malleolus and the hip angle from the vectors trochanter-knee and trochanter-sternum.

Electromyography

Bipolar Ag/AgCl surface electrodes (Ambu Blue Sensor P, Ballerup, Denmark; diameter 9 mm, center-to-center distance 34 mm) were placed over M. soleus (SOL), M. gastrocnemius medialis (GM), M. tibialis anterior (TA), M. rectus femoris (RF), M. vastus lateralis (VL) and M. biceps femoris (BF) of the right leg. The longitudinal axes of the electrodes were in line with the presumed direction of the underlying muscle fibers. The reference electrode was placed on the patella. Interelectrode resistance was kept below 3 kΩ by means of shaving, light abrasion and degreasing of the skin with a disinfectant.

The EMG signals were transmitted via shielded cables to the amplifier (band-pass filter 10 Hz–1 kHz, 1,000× amplified) and recorded with 4 kHz.

Data processing

After removing DC offsets, the EMG signals were rectified. Subsequently, the mean of the EMG and force signals were calculated for each trial (consisting of 60 hops), using the GRF of the right force plate as a trigger signal for the moment of ground contact (GC). Then, the iEMG was calculated by integrating the mean EMG signal of four time intervals based on previous reported latencies and durations of the reflex components (Lee and Tatton 1978; Marsden et al. 1978; Sinkjaer et al. 1999): the preactivity phase (PRE) from 150 ms before GC until GC, the phase of the short latency response (SLR) from 30 ms after GC until 60 ms after GC, the phase of the medium latency response (MLR) from 60 ms after GC until 90 ms after GC and the phase of the late latency response (LLR) from 90 ms after GC until 120 ms after GC (see Fig. 3). The ground contact time (GCT) was determined as the time interval between GC and takeoff. The RFD was calculated as the peak force divided by the time from GC until the force signal reached its peak. The joint angles were determined at the time of GC and the range of motion (ROM) was calculated for the GCT. The right leg's stiffness was calculated according to Günther and Blickhan (2002) as the ratio of the peak GRF and the displacement of the hip marker (greater trochanter) during the time interval from GC until the GRF reached its peak.

Statistics

Group data are presented as means ± standard deviations (SD) unless otherwise stated. The effect of the training on the recorded electromyographic, kinetic and kinematic parameters was evaluated using two-actor analyses of variance, group [2, TG vs. CON] × time [2, pre vs. post], once for the SH and once for the NH. Moreover, the recorded parameters in the SJS were normalized to those of the NH to assess the specificity of the training adaptations. Again, the normalized values were compared using a two-factor analysis of variance, group [2] × time [2]. The false

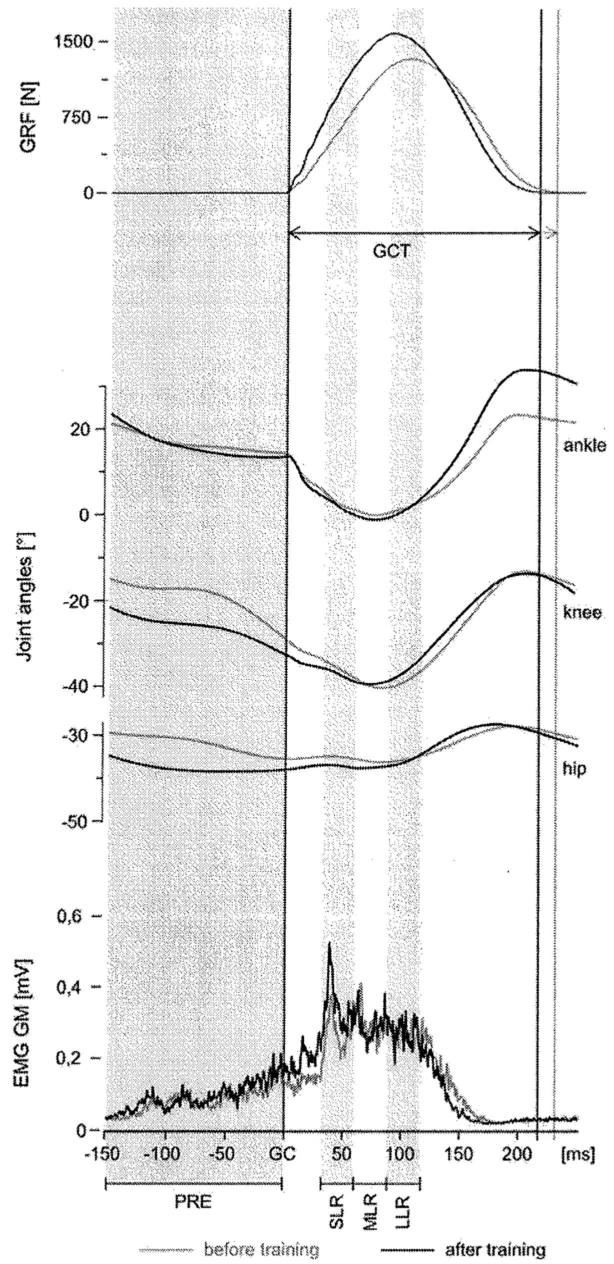

Fig. 3 Averaged forces, joint angles and EMG data of 2 × 60 hops from one TG participant in the sledge jump system. *Black curves* represent the jumps after the training, and the *gray* ones represent the jumps before the training. The ground contact time (GCT) is marked as the time between ground contact and takeoff. Also marked are the relevant EMG phases: PRE 150 ms before GC until GC, SLR 30–60 ms after GC, MLR 60–90 ms and LLR 90–120 ms. For the joint angles, negative values indicate more flexion than that during upright stance

discovery rate was controlled according to the Benjamini–Hochberg–Yekutieli method (Benjamini and Yekutieli 2005). The analyses were executed either by using SPSS 19.0 (SPSS, Inc., Chicago, IL, USA) or simply by using the appropriate formula.

Results

In Table 1a, the absolute peak forces, RFD, leg stiffness and the GCT of the hops in the SJS (right leg) before the training are displayed alongside the relative values after the training period. The analyses of variance revealed a significant interaction group × time for the peak forces, RFD and leg stiffness, i.e., those parameters increased significantly more for the TG than for the CON. For the GCT, the interaction was not significant, but the main effect of the time indicated a significant decrease of GCT after the training period for both groups. The table does not include the values for the NH, since none of the aforementioned parameters changed significantly for the NH except for the main effect of time ($p < 0.01$), i.e., the GCT significantly decreased for both groups, just like for the SH. Table 1b shows the changes of the same parameters, but normalized to the values of the NH, i.e., the SH before the training divided by the NH before the training and the SH after the training divided by the NH after the training. For the RFD, leg stiffness and GCT, the analysis showed a significant interaction of group × time: these parameters changed significantly more for the TG than for the CON.

The iEMG activity of the six leg muscles during four phases (PRE, SLR, MLR and LLR) in the SJS is shown in Table 2. All values are normalized to NH. The analysis of variance revealed no differences: for the interaction group × time or for the main effects.

The joint angles at GC for the hops in the SJS and the ROM during the GCT are presented in Table 3a. Again, neither the interaction nor the main effects showed any significant differences. Table 3b shows the differences between the SH and the NH. Again, no significant changes could be observed. In summary, the motion analysis did not reveal any changes due to the training regimen, when only looking at the hops in the SJS or when comparing them to the hops on the ground.

Discussion

The 4-week training regimen in the SJS significantly and considerably increased the parameters that are regarded as important for the system's use as a countermeasure for microgravity effects, namely the peak forces and the RFD, which are both considered to be very important for the retention of muscle and bone strength. Other parameters such as leg stiffness increased even to the point of being equal to the leg stiffness observed for normal hops on the

Table 1 **a** Mean values of all participants of the peak ground reaction force, the average rate of force development (RFD), the stiffness and the ground contact time (GCT) of the hops in the SJS for the training group (TG) and the control group (CON) before (absolute values) and after the training period (percentages of the respective pre-training values), **b** Same parameters as in A, but normalized to the hops on the ground. For example, the increase from 76 to 84% means that the peak forces of the hops in the SJS before the training period amounted to 76% of the recorded peak forces for the normal hops, whereas after the training they amounted to 84%, thus reducing the differences between the two types of hops from 24 to 16%. The last row contains the results of the analysis of variance

	Peak force	RFD	Stiffness	GCT
(a)				
TG pre	1,279 ± 177 N	13.9 ± 3.8 kN/s	19 ± 5 N/mm	198 ± 29 ms
TG post	+10 ± 18%	+35 ± 58%	+38 ± 62%	−9 ± 12%
CON pre	1,311 ± 280 N	15.2 ± 3.7 kN/s	19 ± 5 N/mm	196 ± 21 ms
CON post	+3 ± 9%	+11 ± 27%	+8 ± 23%	−3 ± 10%
Significance	Group × time	Group × time	Group × time	Time
	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
(b)				
TG pre [%]	76 ± 8	58 ± 15	80 ± 23	136 ± 27
TG post [%]	84 ± 9	72 ± 13	99 ± 17	119 ± 11
CON pre [%]	75 ± 9	58 ± 12	84 ± 21	135 ± 19
CON post [%]	77 ± 8	61 ± 15	83 ± 18	136 ± 22
Significance	n.s.	Group × time	Group × time	Group × time
		$p < 0.05$	$p < 0.05$	$p < 0.05$

Table 2 Mean EMG activity of all participants for the six recorded muscles during four phases (PRE 150 ms before GC until GC, SLR 30–60 ms after GC, MLR 60–90 ms and LLR 90–120 ms) for the two groups

	PRE	SLR	MLR	LLR
SOL pretraining TG [%]	79 ± 26	94 ± 22	114 ± 33	239 ± 146
TG post [%]	84 ± 24	101 ± 17	133 ± 68	185 ± 133
CON pre [%]	91 ± 28	94 ± 26	107 ± 30	199 ± 65
CON post [%]	82 ± 26	104 ± 21	128 ± 33	242 ± 83
GM pretraining TG [%]	71 ± 12	95 ± 20	137 ± 46	373 ± 240
TG post [%]	70 ± 14	106 ± 26	169 ± 87	282 ± 191
CON pre [%]	94 ± 15	102 ± 27	137 ± 53	313 ± 189
CON post [%]	82 ± 22	107 ± 21	156 ± 50	387 ± 216
TA pretraining TG [%]	107 ± 31	110 ± 23	123 ± 36	99 ± 49
TG post [%]	137 ± 38	113 ± 16	126 ± 46	90 ± 60
CON pre [%]	120 ± 27	108 ± 14	130 ± 35	111 ± 38
CON post [%]	129 ± 23	113 ± 13	130 ± 23	91 ± 60
BF pretraining TG [%]	134 ± 46	110 ± 24	95 ± 38	139 ± 86
TG post [%]	89 ± 33	115 ± 32	78 ± 19	87 ± 46
CON pre [%]	125 ± 59	96 ± 44	81 ± 29	106 ± 54
CON post [%]	116 ± 47	114 ± 45	86 ± 30	105 ± 45
VL pretraining TG [%]	120 ± 49	91 ± 46	186 ± 100	169 ± 85
TG post [%]	97 ± 33	91 ± 31	179 ± 115	144 ± 71
CON pre [%]	110 ± 31	85 ± 31	147 ± 69	141 ± 49
CON post [%]	92 ± 28	95 ± 29	188 ± 103	144 ± 51
RF pretraining TG [%]	154 ± 66	66 ± 34	179 ± 112	196 ± 133
TG post [%]	150 ± 48	91 ± 37	194 ± 111	239 ± 211
CON pre [%]	161 ± 43	73 ± 37	146 ± 58	167 ± 87
CON post [%]	163 ± 64	81 ± 45	183 ± 74	178 ± 66

All values refer to the sledge hops normalized to the normal hops

Table 3 **a** Average joint angles of all participants' sledge hops at the time of ground contact (GC) and the range of motion (ROM) from ground contact until takeoff, **b** Differences in the joint angles between the sledge hops and the normal hops

	Ankle	Knee	Hip
(a)[a]			
GC angle TG pre [°]	14 ± 4	−25 ± 9	−26 ± 8
TG post [°]	13 ± 4	−28 ± 9	−27 ± 8
CON pre [°]	10 ± 9	−25 ± 7	−26 ± 6
CON post [°]	10 ± 6	−26 ± 7	−26 ± 6
ROM TG pre [°]	29 ± 7	24 ± 10	13 ± 6
TG post [°]	29 ± 6	24 ± 8	12 ± 6
CON pre [°]	31 ± 5	27 ± 10	13 ± 6
CON post [°]	30 ± 4	27 ± 8	14 ± 4
(b)[b]			
GC angle TG pre [°]	2 ± 4	−6 ± 6	−16 ± 8
TG post [°]	0 ± 2	−9 ± 5	−15 ± 6
CON pre [°]	−2 ± 6	−7 ± 5	−13 ± 6
CON post [°]	−2 ± 4	−9 ± 6	−15 ± 6
ROM TG pre [°]	−1 ± 5	3 ± 8	3 ± 6
TG post [°]	1 ± 5	4 ± 5	3 ± 5
CON pre [°]	0 ± 5	3 ± 7	2 ± 4
CON post [°]	2 ± 4	5 ± 6	4 ± 3

[a] A negative value at GC signifies that the joint was more flexed compared to the upright stance (as it was the case for the knee and the hip); a positive value signifies that the joint was more extended (as it was the case for the ankle joint)

[b] A negative value at GC indicates that the joint was more flexed during the SH than during NH; a positive value indicates a more extended joint. For example, the value −6 for the knee angle at GC means that the knee was flexed on average 6° more during the SH. A negative value for the ROM indicates that the ROM was smaller for the SH

ground, which is a remarkable result considering the brevity of the training regimen (12 training sessions, lasting about 10 min each). The fact that the increase in the peak forces, RFD and stiffness as well as the reduction of the contact times was not only significant when comparing the absolute TG values before and after the training, but also mostly when comparing the values normalized to the hops on the ground indicates that at least part of the training effects are specific to the SJS. Therefore, the effects of the training regimen are probably mostly due to a familiarization with the device, or in other words an improvement in the coordination of the movement due to motor learning. In a previous cross-sectional study with the SJS, we examined the differences between sledge hops and normal hops on the ground (Kramer et al. 2010) and suggested that part of the observed differences were due to the lacking familiarity with the SJS, resulting in a—consciously or unconsciously—cautious approach, i.e., a movement pattern with reduced stiffness (and consequently lower peak forces and longer GCT). The results of the present study support this suggestion because they show that with training, the participants were able to adopt a more natural movement pattern in the SJS, with a high stiffness and consequently high peak forces and a high RFD, whereas the movement pattern on the ground showed no changes.

The remaining differences in the kinetic parameters after the training between the jumps in the SJS and the jumps on the ground are probably due to two main reasons: the first one is the horizontal body position in the SJS, which affects the sensory feedback and the integration of this feedback into the motor program. For example, in the SJS the quadriceps has to be active all the time to keep the lower leg in a horizontal position, whereas it is barely active during the flight phase of normal jumps. Additionally, altered afferent feedback from cervical muscles—which are also very likely to be much more active in the SJS—might have changed the neural control of the muscular activity in the SJS (Gdowski et al. 2000; Manzoni et al. 1979; Noda 1991). These changes in neural control would not occur in a weightlessness environment though. The second probable reason for the remaining kinetic differences is that the main part of the force in the SJS was applied to the participant via the shoulders, which is quite different from the usual distribution over the whole body. This might have caused the aforementioned cautious approach as an injury-prevention strategy and was probably reduced as a result of the training and the familiarization with the SJS, but not entirely eliminated.

Interestingly, some of the recorded parameters were not notably affected by the training. For example, none of the kinematic parameters (the joint angles at ground contact and the ROM during ground contact) showed statistically significant differences. This finding indicates that the force of gravity acting perpendicular to the movement direction in the SJS caused the differences between the hops in the SJS and the normal hops, making them somewhat hard to influence by means of training. Nevertheless, those differences (mainly, more flexion in the knee and hip joint at the time of ground contact) would most likely be heavily reduced or even eliminated when using the SJS as a training device in space, where gravitational forces are absent and thus do not influence the position of the legs.

The recorded EMG parameters were not significantly affected by the training (see Table 2). However, this lack of observable changes may be a result of the high EMG variance rather than an indication that the training had no effect on the neural control of the movement pattern. Although previous studies demonstrated that the preactivity was dependent on the load and the induced GRF

(Gollhofer and Kyröläinen 1991), the differences in the GRF before and after training in the present study might not be big enough to cause significant changes in the preactivity and other EMG parameters. In any case, the differences between the SH and the NH were already quite small before the training period, especially when considering the high EMG variance. For example, the values for the SLR showed no significant differences between the two types of hops, before or after the training period. Even if some EMG parameters appear to differ to a high extent (like the MLR and the LLR in some recorded muscles, see Table 2), this seemingly big difference is mainly due to the longer GCT in the SJS, since the EMG activity in the late phases of the SH is still high, whereas the EMG activity of the NH has already returned to a low base level. The finding that the preactivity of some of the recorded muscles (mainly the knee extensors) was higher for the jumps in the SJS than for those on the ground is probably due to the fact that the legs have to be actively kept up in the horizontal position, which is not the case for normal jumps on the ground. But like the observed differences in some of the kinematic parameters, these differences might disappear in a weightlessness environment.

In conclusion, the present study showed that existing differences between jumps in the sledge jump system and normal jumps on the ground were significantly reduced or even disappeared after only 4 weeks of training in the SJS. The peak forces and the RFD in the sledge jump system after the training were almost comparable to those of normal reactive jumps. Considering the fact that reactive jumps produce some of the highest peak forces and RFD of all exercise modes, jumps in the SJS provide peak forces and RFD that are much higher than those attained during everyday activities, thus inducing high strains and strain rates. In addition, a reactive jump is a highly dynamic movement that requires a well-timed activation and coordination of the muscles as well as the integration of a multitude of sensory feedback. Therefore, the SJS seems to be a promising integrated countermeasure for at least some of the degrading effects of prolonged microgravity on both the muscles and bones of the lower extremities and the sensorimotor system.

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Conflict of interest The authors declare that they have no conflict of interests.

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