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Leg stiffness can be maintained during reactive hopping despite modified acceleration conditions

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A B S T R A C T

Aim: The aim of the present study was to evaluate reactive hops under systematically modified acceleration conditions. It was hypothesized that a high preactivity of the leg extensors and phase-specific adjustments of the leg muscle activation would compensate the alterations caused by the various acceleration levels in order to maintain a high leg stiffness, thus enabling the jumper to perform truly reactive jumps with short ground contact times despite the unaccustomed acceleration conditions.
Methods: Ground reaction forces (GRF), kinematic and electromyographic data of 20 healthy subjects were recorded during reactive hopping in a special sledge jump system for seven different acceleration levels: three acceleration levels with lower than normal gravity (0.7*g*, 0.8*g*, 0.9*g*), one with gravitational acceleration (1g) and three with higher acceleration (1.1g, 1.2*g*, 1.3*g*).
Results: The increase of the acceleration from 0.7*g* to 1.3*g* had no significant effect on the preactivity of the leg extensors, the leg stiffness and the rate of force development. However, it resulted in increased peak GRF (+15%), longer ground contact time (+10%) and increased angular excursion at the ankle and knee joints (+3°).
Discussion: Throughout a wide acceleration range, the subjects were able to maintain a high leg stiffness and perform reactive hops by keeping the preactivity constantly high and adjusting the muscle activity in the later phases. In consequence, it can be concluded that the neuromuscular system can cope with different acceleration levels, at least in the acceleration range used in this study.

Introduction

The stretch–shortening cycle (SSC) has been studied extensively (Bosco et al., 1982; Finni et al., 2001; Komi and Gollhofer, 1997). It can be defined as the stretching of a preactivated muscle–tendon unit (MTU), immediately followed by a shortening action of the muscle (Komi, 1984). The SSC is characterized by a high efficiency due to a potential storage of energy in the elastic elements of the MTU (Asmussen and Bonde-Petersen, 1974; Gollhofer, 1987; McCaulley et al., 2007) and is often described as the natural type of muscle action, as it is constitutive for everyday activities such as running or jumping, as well as for many sports. Several studies suggest that the prerequisites for a storage of energy in the MTU during reactive jumps using the SSC are the absence of heel contact (Schmidtbleicher and Gollhofer, 1982; Bobbert et al., 1987), and above all a high muscle stiffness, which in turn requires a high preactivation of the leg extensor muscles (Ishikawa and Komi, 2004; Komi and Gollhofer, 1997). If these requirements are not met, the strain energy cannot be stored in the elastic components of the MTU and instead dissipates as thermal heat. In consequence, many studies have tried to identify optimal conditions that allow the execution of reactive jumps with high leg stiffness. It has been shown that a number of factors determine the range of optimal conditions for reactive jumps: these factors include the falling height (Bosco and Komi, 1979; Kyröläinen and Komi, 1995; Schmidtbleicher and Gollhofer, 1982), the additional mass that is attached to the jumper (Bosco and Komi, 1979; Gollhofer and Kyröläinen, 1991) and the kinetic energy just prior to ground contact, which is often considered to be the most important factor, as it includes both the mass and the falling height (Bubeck, 2002).

One factor that seems to limit the possibility to perform reactive jumps to a particularly narrow range is the acceleration acting on the jumper: there are only a few studies, but they all suggest that jumps with accelerations both above 1*g* and below 1*g* lead to inferior results compared to jumps with gravitational acceleration. For example, Avela et al. (1994) employed a "lifting

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block system" using weights and counterweights to modulate the effective acceleration acting on the jumper. They compared two different accelerations (0.8*g* and 1.2*g*) to the normal acceleration of 1*g* and observed lower ground reaction forces (GRFs), longer ground contact times (GCT) and lower preactivity of the leg extensors, both for the jumps with an acceleration of 0.8*g* and the ones with an acceleration of 1.2*g*. Consequently, the authors concluded that "all the results emphasized considerable adaptation of the neuromuscular system to the normal gravity condition" (Avela et al. (1994). Albeit using different systems for the variation of the acceleration, other authors came to similar conclusions (Bubeck, 2002; Cavagna et al., 1972; Gollhofer and Kyröläinen, 1991), and Gollhofer and Kyröläinen suggested that mainly the low preactivity of the leg extensors was responsible: "the centrally programmed activity prior to the contact can be seen as the decisive mechanism in the regulation of the stiffness behavior of the tendomuscular system" (Gollhofer and Kyröläinen, 1991). However, it remains unclear if the observed optimal jump performance at the acceleration of 1g is really due to an evolutionary adaptation to the gravitational acceleration, or if the systems modulating the acceleration used in the aforementioned studies were simply not adequate for the task. For example, the system used by Bubeck (2002) could vary the acceleration only by also varying the inertia of the jumper, which probably had a considerable confounding effect on the results. Likewise, the abrupt change of the acceleration at the moment of ground contact that was inherent to the systems used by Gollhofer and Kyröläinen (1991) and Avela et al., 1994 had probably also a strong effect on the results.

Therefore, the purpose of the present study was to assess the effects of modulated acceleration with a new system which was already validated in a previous study (Kramer et al., 2010) and which allows a variation of the acceleration without changing the inertia or inducing sudden changes of the acceleration acting on the jumper. It was hypothesized that a high preactivity of the leg extensors and phase-specific adjustments of the leg muscle activation would compensate the alterations caused by the various acceleration levels in order to maintain a high leg stiffness, thus enabling the jumper to perform truly reactive jumps with short ground contact times and a high rate of force development despite the unaccustomed acceleration conditions ranging from 0.7*g* to 1.3*g*.

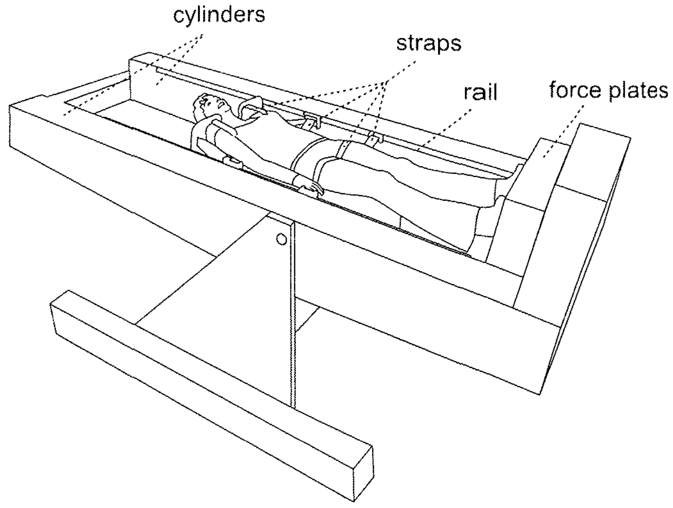

Fig. 1. Sledge jump system in the horizontal position. The participant is fixed to the wooden sledge with straps. The straps are attached to the rails and can slide in the direction of the rails. The participant stands on two force plates (separated, one for each foot). Reprinted from Kramer et al.,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

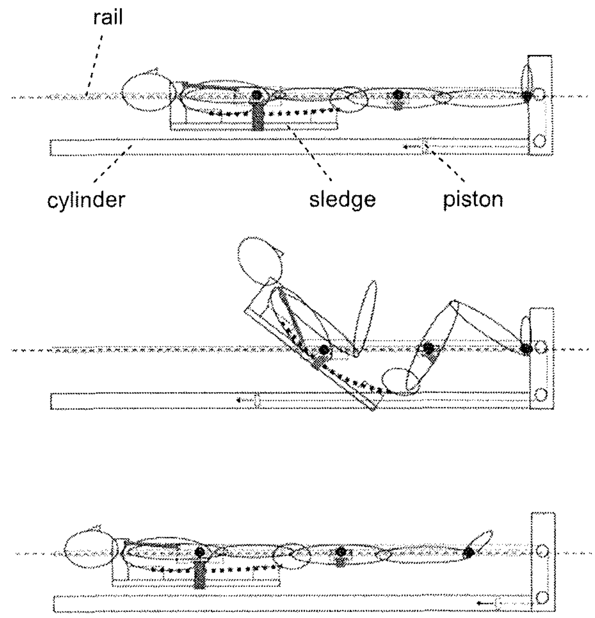

Fig. 2. Longitudinal section of the SJS. The two low-pressure cylinders pull the participant onto the force plates. The second drawing illustrates the freedom of movement in the ankle, knee and hip joint (the downward movement of the hip is not constrained by the cylinders like the drawing might suggest,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

Methods

Subjects: Twenty subjects (4 females, 16 males) volunteered to participate in this study. The participants were healthy, physically active students at the department of sports science. 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 Declaration of Helsinki. Their mean (±standard deviation, SD) height, body mass and age were 177±7 cm, 74±8 kg and 23±3 years, respectively.

Experimental design: A single-group repeated-measures study design was used to examine differences between hops in the SJS with 7 different accelerations (0.7, 0.8, 0.9, 1, 1.1, 1.2 and 1.3*g*). After a 10-min warm-up phase (consisting of running, tapping and hopping), the hops were performed with the instruction "jump as stiff as possible". One trial consisted of 40 hops with a 2-min break after 20 hops. Before each trial, the participants performed 10 hops with the acceleration of the subsequent 40 hops in order to familiarize the participants with the new acceleration condition. The hops were performed bare-footed on two force plates (Leonardo®, Novotec Medical, Germany). The ground reaction forces (GRFs) were recorded separately for the right and the left foot and synchronized to the electromyograpic (EMG) signals. The order of the test conditions was balanced between subjects to control confounding effects such as fatigue. In addition, the participants were given at least 3 min of rest in between trials.

Sledge jump system: The SJS (see Figs. 1 and 2) was developed by Novotec Medical (Pforzheim, Germany). For a detailed description, see Kramer et al. (2010). Basically, the subject can jump in the system with hardly any restrictions concerning the joint movements, allowing almost natural jumps. Since the movement direction is along a horizontal axis, the forces generated by the two low-pressure cylinders substitute the gravitational force. The pressure was adjusted in a way that the forces produced by the cylinders matched the designated fraction of the subject's weight, e.g. an acceleration of 0.7*g* for a subject with a weight of 750 N was achieved by setting the force to 750 N × 0.7 = 525 N.

Kinematics: The jumps were recorded with a motion capturing system (Vicon, UK) using ten 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 (ankle, knee and hip). An additional marker on the sledge was used to determine the jumper's velocity.

Electromyography: Bipolar surface electrodes (Ambu Blue Sensor P, Denmark) were placed over M. soleus (SOL), M. gastrocnemius medialis (GM), M. tibialis anterior (TA), M. rectus femoris (RF), M. vastuslateralis (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. Interelectrode resistance was kept below 3 kΩ by means of shaving, light abrasion and degreasing of the skin. The EMG signals were transmitted via shielded cables to the amplifier (band-pass filter 10 Hz–1 kHz, 1000 × amplified) and recorded with 4 kHz.

Data processing: After removing DC offsets, the EMG signals were rectified. Afterwards, the means of the EMG and force signals were calculated for each trial, 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 4 time intervals, based on previous reported latencies and durations of the reflex components (Lee and Tatton, 1978; Sinkjaer et al., 1999): the preactivity phase (PRE) from 50 ms before ground contact (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 until 90 ms and the phase of the long-latency response (LLR) from 90 ms until 120 ms (see Fig. 3). To ensure inter-subject comparability, the iEMG during each phase was normalized to the subject's iEMG from −150 ms to +120 ms, and the GRF was normalized to the subject's body weight. The rate of force development (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 angular joint excursions were calculated from GC until the GRF reached its peak. The leg stiffness was calculated according to Günther and Blickhan (2002) as the ratio of the peak GRF to the displacement of the hip marker (greater trochanter) during the time interval

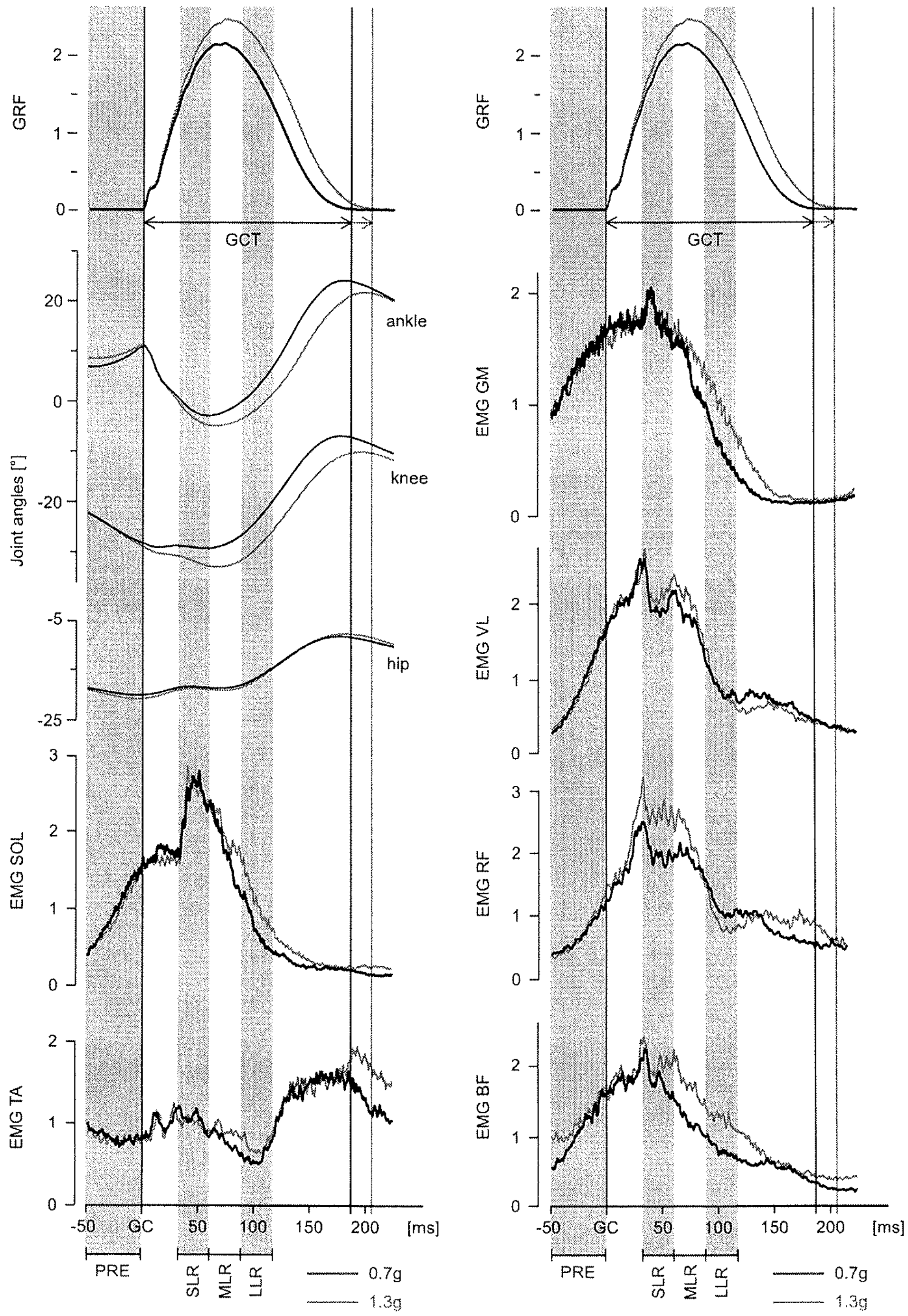

Fig. 3. Averaged ground reaction forces (GRFs, right leg), joint angles and EMG data for all participants during two acceleration levels. Black lines represent the hops with an acceleration of 0.7g, the gray ones represent the hops with 1.3g. The ground contact time (GCT) is marked as the time between ground contact and takeoff. Also marked are the relevant EMG phases: PRE 50 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 in comparison to upright stance. To ensure inter-subject comparability, the GRF was normalized to the body weight and the EMG to the average EMG activity from −150 ms to +120 ms.

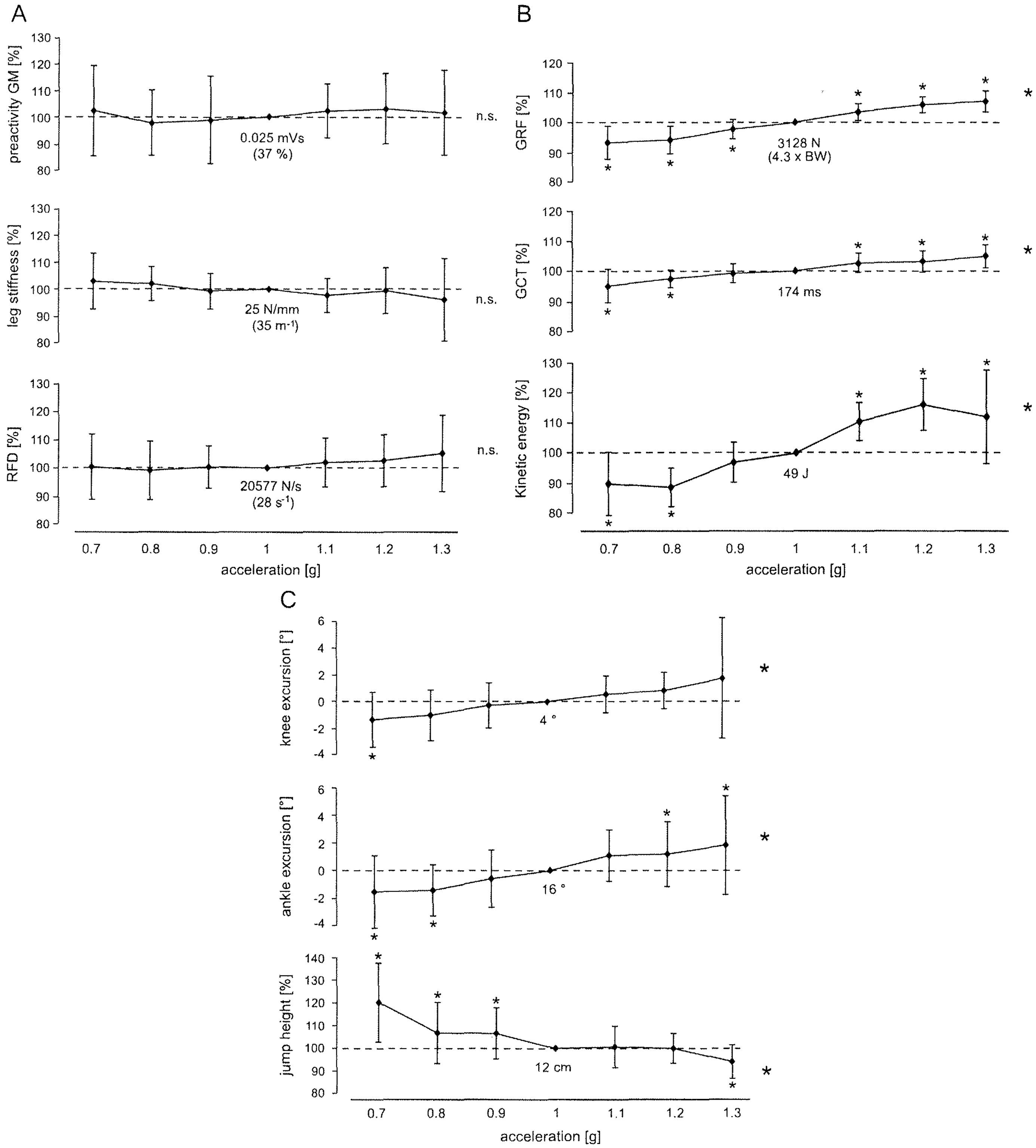

Fig. 4. A. Grand mean of the most important parameters of a reactive jump for all participants for the 7 acceleration levels from 0.7*g* to 1.3*g*: preactivity of the leg extensors (the medial gastrocnemius is shown as a representative example), leg stiffness and rate of force development (RFD), all normalized to the respective 1*g* value. For the 1*g* condition, both the absolute values and the relative values (i.e., normalized to the iEMG from −150 ms to +120 ms in the case of preactivity and to the body weight in the case of leg stiffness and RFD) are displayed. The acceleration has no statistically significant influence on any of the 3 parameters. B. Grand mean of the kinetic data for the seven acceleration levels: peak ground reaction force (GRF, both legs), ground contact time (GCT) and kinetic energy just prior to ground contact, all normalized to the respective 1g value. The acceleration has a statistically significant influence on all 3 parameters (big * symbol, denoting a significant ANOVA result). A small * symbol denotes a statistically significant difference compared to the 1*g* condition. C. Grand mean of the kinematic data for the 7 acceleration levels: knee excursion in the eccentric phase of the jump, i.e. from ground contact until the force curve reached its peak, ankle excursion in the eccentric phase of the jump and jump height. The acceleration has a statistically significant influence on all 3 parameters.

Conflict of interest statement

The authors did not have any financial and personal relationships with other people or organizations that could inappropriately influence the study.

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