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ORIGINAL ARTICLE

The relationship between leg stiffness, forces and neural control of the leg musculature during the stretch-shortening cycle is dependent on the anticipation of drop height

Michael Helm[1] · Kathrin Freyler[1] · Janice Waldvogel[1] · Albert Gollhofer[1] · Ramona Ritzmann[1]

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Abstract

Purpose This study aimed at investigating how prior knowledge of drop heights affects proactive and reactive motor control in drop jumps (DJ).

Methods In 22 subjects, the effect of knowledge of three different drop heights (20, 30, 40 cm) during DJs was evaluated in seven conditions: three different drop heights were either known, unknown or cheated (announced 40 cm, but actual drop height was 20 cm). Peak ground reaction force (F_{max}) to body weight (BW) ratio (F_{max}/BW) and electromyographic (EMG) activities of three shank and five thigh muscles were assessed 150 ms before and during ground contact (GC). Ankle, knee and hip joint kinematics were recorded in the sagittal plane.

Results Leg stiffness, proactive and reactive EMG activity of the leg muscles diminished in unknown and cheat conditions for all drop heights (7–33% and 2–26%, respectively). Antagonistic co-activation increased in unknown (3–37%). At touchdown, increased flexion in knee (~ 5.3° ± 1.9°) and hip extension (~ 2° ± 0.6°) were observed in unknown, followed by an increased angular excursion in hip (~ 2.3° ± 0.2°) and knee joints (~ 5.6° ± 0.2°) during GC ($p < 0.05$). Correlations between changes in activation intensities, joint kinematics, leg stiffness and F_{max}/BW ($p < 0.05$) indicate that anticipation changes the neuromechanical coupling of DJs. No dropouts were recorded.

Conclusion These findings underline that anticipation influences timing and adjustment of motor responses. It is argued that proactive and reactive modulations associated with diminished activation intensities in leg extensors are functionally relevant in explaining changes in leg stiffness and subsequent decline in performance.

Keywords Neuromuscular · Jump · Electromyography · Reactive · F_{max} · Prediction · Unpredicted

Abbreviations

BF	M. biceps femoris
BW	Body weight
CNS	Central nervous system
COM	Center of mass
DJ	Drop jump
Fmax	Peak ground reaction force
GC	Ground contact
GCT	Ground contact time
GL	M. gastrocnemius lateralis
Gmax	M. gluteus maximus
iEMG	Integrated electromyographic activity
LLR	Late-latency response
MLR	Medium-latency response
MTU	Muscle tendon unit
MVC	Maximal voluntary contraction
PRE	Pre-activation
RF	M. rectus femoris
rmANOVA	Repeated-measures analysis of variance
SD	Standard deviation
SLR	Short-latency response
SOL	M. soleus
SSC	Stretch-shortening cycle
TA	M. tibialis anterior
VL	M. vastus lateralis
VM	M. vastus medialis

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✉ Michael Helm
michael.helm@sport.uni-freiburg.de

[1] Institute of Sport and Sport Science, University of Freiburg, Schwarzwaldstr. 175, 79117 Freiburg, Germany

Introduction

Anticipation plays a major role in the execution of human motor tasks, thereby affecting the timing of muscular activations, their efficiency and overall performance (Greenwood and Hopkins 1976; Leukel et al. 2012; Mayer et al. 2007; Schmidt 1968). In reactive movements, characteristics of jumping behaviour are manifested by performance parameters such as jumping height, rate of force development and maximal ground reaction forces (Komi 2003; Komi and Gollhofer 1997). Thereby, an accurately anticipated neural control is required to deliver a motor response simultaneously with the event of touchdown. The muscle mechanics underlying these reactive movements make up the stretch-shortening cycle (SSC) (Komi 2003; Komi and Gollhofer 1997). The SSC is defined by the stretching of the preactivated musculature in the eccentric phase of the movement, followed by an immediate muscle shortening in the concentric phase until push-off (Komi 1984, 2003; Taube et al. 2012b). The ability of the SSC to store energy in the elastic elements of the muscle tendon unit (MTU) depends upon a preactivated MTU and allows for exceedingly high forces during the push-off phase (Ishikawa and Komi 2004; Komi 2003; Komi and Gollhofer 1997). The associated spring-mass model relies on leg stiffness as a common parameter used to characterise leg function within the class of reactive movements, such as running and hopping (Silder et al. 2015). In this model, the legs are treated as massless linear springs, with leg stiffness as the quotient of the peak vertical ground reaction force and the associated vertical displacement of the hip marker (Serpell et al. 2012).

Variability in impact loading due to variability in drop heights is of significance for daily activities, as well as sporting activities (e.g. parachuting, gymnastics, cross-country-running and parkour), and is described as a key determinant of performance of fast reactive movements. Scientific interest in modifications of impact loads on the SSC and its neuromechanical control, joint kinematics and performance efficiency has increased in the last decades (Arampatzis et al. 2004; Farley et al. 1998; Ferris and Farley 1997; Gollhofer and Kyröläinen 1991; Ishikawa and Komi 2004; Lesinski et al. 2018; Leukel et al. 2009; Márquez et al. 2014; Moritz and Farley 2005; Prieske et al. 2013, 2015; Sousa et al. 2007; Taube et al. 2012b). Published articles have dealt with scenarios in which drop heights were known to the subjects prior to performing drop jumps; however, none dealt with scenarios in which drop heights were unknown or misleadingly announced to the subjects.

Previous research reveals that higher neuromuscular activity in the preactivation phase is a determinant for an enhanced performance, as the increased muscular stiffness it creates also increases storage and release of energy during the SSC (Gollhofer and Kyröläinen 1991). Consequently, both preactivation and sensibility of the muscle spindles based on α–γ co-activation are the main prerequisites for enhanced reflex activities occurring during the eccentric phase of the movement, thus determining muscular activation during the later phases prior to push-off (Hoffer and Andreassen 1981; Sinkjaer et al. 1988). Leg stiffness has been shown to be a key factor in the performance of fast reactive movements, with reference to studies that observed changes of leg stiffness in athletes performing drop jumps, hopping or running tasks (Arampatzis et al. 2001b; Brauner et al. 2014; Coleman et al. 2012; Farley et al. 1998; Farley and González 1996). Therefore, leg stiffness is strongly determined by leg extensors' level of preactivity (Gollhofer and Kyröläinen 1991). Leg extensors are generally known as anti-gravity muscles and comprise the plantar flexors, knee and hip extensors (Ritzmann et al. 2016).

However, the effect of anticipation on leg stiffness and the associated neural control of the leg's musculature have yet to be analysed. Predictability experiments revealed three distinct modalities attributed to an increased level of difficulty: (1) known, (2) unknown or (3) wrongly expected conditions (Horak et al. 1989). The latter modality, 'wrongly expected', has been manifested as a cheat condition, being the most difficult to manage among all conditions related to diminished anticipation and surprising motor consequences (Horak et al. 1989). The objective of the study, therefore, was to examine the effects of anticipation on leg muscular activations, leg stiffness, forces and joint kinematics during drop jumps performed from low, medium and high heights. Thus, the drop height was either known, unknown or deliberately announced wrongly to the subjects.

It was, therefore, hypothesised that reduced leg stiffness would occur in the unknown and cheat conditions due to a reduced preactivation of the anti-gravity muscles, leading to a diminished muscular response in the shank and thigh musculature in the reactive phase (Ritzmann et al. 2016). Greater joint excursions coupled with enhanced antagonistic co-activations were expected to occur in both the unknown and cheat conditions due to a diminished preactivation of musculature, leading to an inability to store elastic energy and reuse it efficiently in the push-off phase. Thus, large performance decrements with reference to the maximal force and jump height were expected to occur in both the unknown and cheat conditions.

Materials and methods

Experimental design

A single-group repeated-measures study design was established to evaluate the interaction effects of drop height anticipation on leg stiffness, joint kinematics, neuromuscular activity and force parameters in drop jumps.

Participants

Twenty-two participants were recruited in this study (10 women, 12 men; age 24.5 ± 3 years; weight 69.9 ± 10 kg; height 175.8 ± 8.1 cm; shank length: 41.2 ± 2.4 cm). The sample size was estimated by means of a power analysis using G*Power (Erdfelder et al. 1996), based on a previously executed pilot study ($f = 0.90$; $\alpha = 0.05$; power = 0.90). All subjects gave written informed consent to the experimental procedure, which was approved by the ethics committee of the University of Freiburg (15/13) and was in accordance with the latest revision of the Declaration of Helsinki. Exclusion criteria were pregnancy, sickness, injuries, vestibular or proprioceptive dysfunction, previous surgeries on the left or right leg, neuro-degenerative diseases or single events associated with neural dysfunctions and an age > 35 years. Only subjects from the Institute of Sports and Sport Science of the University of Freiburg were recruited, aiming at a homogenously healthy and sportive subpopulation. There were no dropouts.

Experimental process

To assess variations in response to anticipation, subjects performed drop jumps barefoot from a height-adjustable platform on top of two force plates for both the right and left feet (AMTI OR6-6-OP-2K-CTT, Watertown, MA, USA). The drop jumps occurred in one of three different situations (Fig. 1): the subjects either (1) knew from which height they performed a drop jump ('known condition'), (2) the drop height was unknown to them ('unknown condition') or (3) they were deliberately misinformed about the actual drop height ('cheat condition', performed only once at the end of the experiment). For the cheat condition, the investigator informed subjects that they would be jumping from a drop height of 40 cm, when in actuality the drop height was only 20 cm. Subjects performed 10 drop jumps for each condition with the drop heights being 20 (low), 30 (medium) and 40 (high) cm. After every 15 jumps, the participants took 5-min breaks, to reduce the effects of fatigue. Conditions were

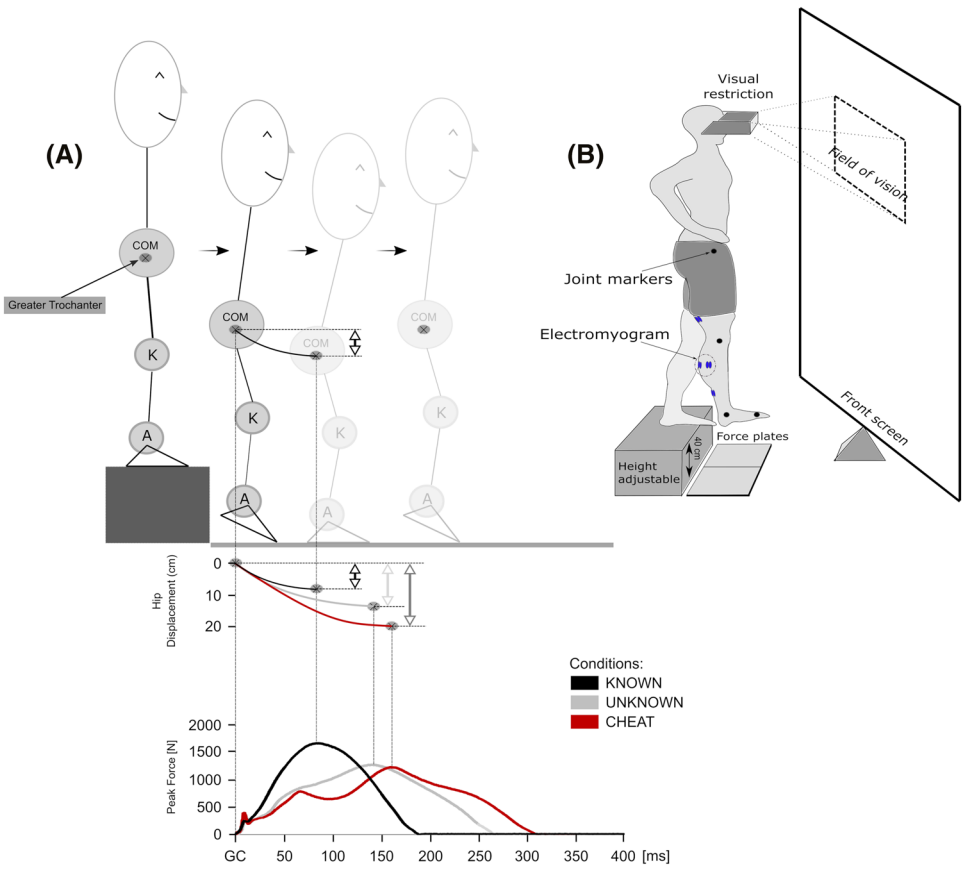

Fig. 1 Schematic of a drop jump indicating changes in hip displacement (greater trochanter) by means of changes in centre of mass (COM) as well as knee (K) and ankle (A) deflections in the known, unknown and cheated condition of one exemplary subject. Corresponding peak forces are presented for each condition from GC until 400 ms after GC. Leg stiffness is described by the ratio of peak force to the displacement of the greater trochanter

performed in a software-generated random order (Labview, Imago, Pfitec, Freiburg). To make certain that subjects performed drop jumps reactively according to given scientific standards, they were instructed to perform drop jumps with stiff legs not giving away in the knees, short ground contact (GC) time and a fast maximal push-off from the ground (Kramer et al. 2012). Furthermore, subjects were instructed to always start the drop jump with the right leg, to keep their gaze fixed on a blank screen (280 cm × 280 cm) placed 2 m in front of them, to prevent collection of visual clues. To further assure that the subjects' field of view was restricted to the front, subjects wore a cap consisting of blinkers as well as dribbling goggles to prevent subjects' from viewing the ground surface. Between each trial, the height-adjustable platform was arbitrarily raised and lowered mechanically to confuse the subjects about the platform's actual elevation while the subject had his or her eyes closed (Fig. 1). This setup prevented subjects from cheating by picking up environmental clues that would have falsified the study's results.

Crucial limitations for discarding a jump in the known condition were based upon previous studies (Bobbert et al. 1987a, b; Gollhofer and Kyröläinen 1991; Lesinski et al. 2016, 2018). Ensuring the validity and reliability of jumps we set the following exclusion criteria: (a) subject lowered their centre of mass when leaving the platform before drop down, (b) knees being significantly flexed at initial GC and during GC, both visually observed by a trained operator, (c) ground contact time (GCT) > 350 ms, (d) subject landed outside the force platform area or two feet landed on the same platform or (e) hands were not placed on the iliac crest (Bobbert et al. 1987a, b; Gollhofer and Kyröläinen 1991; Lesinski et al. 2016, 2018). A drop jump was rejected in the unknown condition based upon different characteristics than those of the known condition, as the drop jumps in the unknown condition were expected to consist of longer GCTs or greater knee excursions due to the uncertainty. Drop jumps in the unknown condition were excluded when subjects (a) landed outside the platform area, (b) anticipated or saw the ground, (c) lowered their centre of mass on purpose before leaving the platform, or (e) did not position their hands on the iliac crest.

Paradigms

With the intention of keeping a strong test reliability, subjects were given a set of standardised sentences that were mentioned just before the jump was executed as follows:

- *Known condition* 'This time you know about the drop height. You will perform a drop jump from high/medium/low drop height. Get ready to jump.'
- *Unknown condition* 'You are not aware of the drop height. Get ready to jump.'
- *Cheat condition* 'This time you know about the drop height. You will perform a drop jump from a high drop height. Get ready to jump.' In fact, the participant jumped from a low drop height, instead of a high drop height.

Testing preparation

Before measurements, subjects performed three isometric maximal voluntary contractions (MVCs) for each recorded muscle (Roelants et al. 2006). According to Roelants et al. (2006) and Wiley and Damiano (1998), the trial with the highest electromyographic activity (EMG) signal was used for data normalisation. The MVCs were performed against resistance for 3 s interspersed with recovery pauses of 2 min between trials and repetitions (Roelants et al. 2006). Body positions during MVCs were firmly supervised by the authors and controlled with standardised hip, knee and ankle joint angles (Freyler et al. 2016). Furthermore, antagonistic muscle activation was monitored, and trials were repeated when antagonists were activated. This was defined as an EMG activity that lasts for more than 25 ms and is two standard deviations away from the mean baseline EMG value (Fong et al. 2015; Konrad 2006).

The MVCs were executed as follows: for the *m. soleus* (SOL) and *m. gastrocnemius lateralis* (GL), subjects were seated with a knee angle of 90°, ankle angle of 110° and heel touching the ground (Hermens et al. 2000). Subjects completed maximal plantar flexions with inelastic straps providing resistance at the distal region of the rectus femoris, to minimise knee joint movement in the sagittal or frontal plane. *M. tibialis anterior* (TA) MVCs were executed in an upright stance with the subject's knee being extended and an ankle angle of 90° (Wiley and Damiano 1998). A maximal ankle dorsiflexion was performed against external resistance, which the investigator applied at the region of the mid-foot. The *m. rectus femoris* (RF), *m. vastus medialis* (VM) and *lateralis* (VL) MVCs were assessed with a knee and ankle angle of 90° in a seated position, while the subject's feet had no contact with the ground (Wiley and Damiano 1998). Subjects had to perform a hip flexion for RF MVC and a knee extension for VM and VL MVC. *M. biceps femoris* (BF) MVCs were measured with subjects in an upright stance, knee bent at 90° and ankle joint relaxed. Subjects performed a knee flexion against external resistance, applied by the investigator, at the distal region of the lower leg (Konrad 2006). For the MVC measurement of *m. gluteus maximus* (Gmax), subjects laid supine, knees bent at 45° and feet placed flat on the floor (Wiley and Damiano 1998). An inelastic strap was placed around the subject at the region of the anterior iliac spine. The subjects raised their hips off the ground and maximally pushed against inelastic straps while contracting the gluteal musculature.

Measurements

Force recordings

Peak ground reaction forces (F_{max}) for the left and right leg were recorded with a force plate with a sampling frequency of 2 kHz. GC was determined by a software as soon as the ground reaction force raised above 20 N, sending a digital trigger to synchronize electromyographic and kinematic recordings.

Kinematic recordings

A high-speed camera (Basler ace acA1920, Basler AG., 22926 Ahrensburg, sampling frequency of 100 Hz) with a resolution of 1920 × 1200 px was utilised to record 2D movements of the right limb segments, placed at a distance of 3 m from the force platform, perpendicular to the sagittal plane (Gambelli et al. 2016). Markers were taped on the participants' skin on the following anatomical landmarks, from cranial to caudal: iliac crest, greater trochanter, femoral condyle, lateral malleolus, and the fifth metatarsal (Gambelli et al. 2016). To further increase practical accuracy, always the same trained investigator performed the placement of the markers on the predefined anatomical landmarks. The software SIMI Motion by SIMI Reality Motions System GmbH (85716 Unterschleißheim, Germany) was employed for the kinematic analyses.

Electromyography

Bipolar Ag/AgCl surface electrodes (Ambu Blue Sensor P, Ballerup, Denmark; diameter 9 mm, centre-to-centre distance 34 mm) were positioned on the GL, SOL, TA, BF, RF, VL,VM and Gmax of the right leg according to SENIAM (Hermens et al. 2000). It was assured that the longitudinal axes of the electrodes were in line with the direction of the underlying muscle fibres. By means of shaving, light abrasion, degreasing, and disinfection of the skin, inter-electrode resistance was kept below 2 kΩ. The reference electrode was placed on the tibia. The EMG signals were transmitted to the amplifier (band-pass filter of 0.1–1.3 kHz, amplified 500×) via shielded cables and recorded with 2 kHz; cables were taped to the skin.

Data processing

The leg stiffness (N/m) was calculated (Günther and Blickhan 2002; Hughes and Watkins 2008; Kramer et al. 2012) as the ratio of the F_{max} to the displacement of the hip marker (greater trochanter) during the time interval from GC until F_{max}. Drop down was controlled by the maximal vertical COM displacement from push-off to touchdown; data are illustrated in Table 1.

The ratio of F_{max} to body weight (BW) (F_{max}/BW) was evaluated to determine the loading force, hence the relative load on the human body that was generated during a drop jump.

The angles (°) of the ankle, knee and hip joints were also determined at the event of GC, and the angular joint excursions (°) and angular velocities (°/s) were calculated from GC until F_{max}.

For each recorded muscle, the EMG was rectified, averaged, integrated (iEMG) and divided into four time intervals based on prior reported latencies and durations of the reflex components (Lee and Tatton 1975; Marsden et al. 1978; Sinkjaer et al. 1999): the preactivation phase (PRE) (150–0 ms before GC), the short-latency response (SLR) (30–60 ms after GC) (Rinalduzzi et al. 2015), the medium-latency response (MLR) (60–85 ms after GC), and the long-latency response (LLR) (85–120 ms after GC) (Lee and Tatton 1975; Taube et al. 2006). Subsequently, iEMGs were normalised to the respective MVC. Furthermore, co-activation was defined as the ratio of the activation level of TA and the activation level of SOL (TA/SOL) as well as the ratio of the activation level of BF and RF (BF/RF), and was calculated for preactivation and SLR, MLR and LLR phases (Hoffrén et al. 2011).

Statistics

The statistical analyses were executed using SPSS 23.0 (SPSS Inc., Chicago, Illinois). The effect of anticipation with the specifications known and unknown conditions on the variables F_{max}/BW, EMG activity, co-activation, joint angles and deflections and leg stiffness were evaluated using a two-factor repeated measures analysis of variance (rmANOVA) [anticipation (2) × drop height (3)]. Data followed a normal distribution, as evaluated using the Kolmogorov–Smirnov test prior to analysis. The Greenhouse–Geisser correction was used if the assumption of sphericity, as measured via Mauchly's test, was violated. The false discovery rate was controlled according to the Benjamini–Hochberg–Yekutieli method, to correct for multiple testing. Benjamini–Hochberg–Yekutieli conceptualises the rate of type I errors (Benjamini and Hochberg 1995; Benjamini and Yekutieli 2005). The level of significance was set to $p < 0.05$ and effect sizes (partial eta-squared, η^2) were calculated. Hereby an effect size of < 0.01 was interpreted as a small effect, a medium effect size related to an effect size between > 0.01 and < 0.14 and a large effect size agreed with an effect size of > 0.14 (Cohen 1988; Leonhart et al. 2004). The cheat condition was compared to the known condition for the 20 cm jump height with Student's *t* tests and the false discovery rate was

Table 1 The effect of anticipation on drop jumps: F_{max}/BW, leg stiffness, jump heights as well as maximal COM (hip marker) displacements prior to the landing from height-adjustable platform

Parameter	Low			Medium		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction effect (A x Dh)
Forces										
F_{max}/BW (N/kg)	23.9 ± 4.8	24.2 ± 5.8	26.4 ± 12.9	28.5 ± 7.0	24.2 ± 5.6**	35.2 ± 10.2	35.1 ± 9.6	**$F(1, 21) = 4.85$, $p = 0.04$, $\eta_p^2 = 0.19$**	**$F(1.4, 28.4) = 1.8$, $p < 0.001$, $\eta_p^2 = 0.77$**	**$F(2, 42) = 20.7$, $p < 0.001$, $\eta_p^2 = 0.5$**
Kinematics										
Leg stiffness (N/m)	12,671.1 ± 3916.6	9963.1 ± 3173.0	8430.3 ± 2742.4*	15,577.1 ± 5637.9	11,275 ± 4205.5*	18,732.2 ± 6661.5	17,339.6 ± 6638.6	**$F(1, 17) = 23.81$, $p < 0.001$, $\eta_p^2 = 0.58$**	**$F(1.2, 20.1) = 40.08$, $p < 0.001$, $\eta_p^2 = 0.70$**	**$F(1.4, 24.0) = 5.0$, $p = 0.03$, $\eta_p^2 = 0.23$**
Jump height (cm)	12 ± 5	9 ± 5*	17 ± 7	14 ± 5	12 ± 6	13 ± 4	10 ± 4*	**$F(1, 21) = 34.0$, $p < 0.001$, $\eta_p^2 = 0.62$**	**$F(2, 42) = 10.9$, $p < 0.001$, $\eta_p^2 = 0.34$**	$F(2, 42) = 0.7$, $p = 0.52$, $\eta_p^2 = 0.03$
COM displacement (platform) (m)	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.02	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.02	0.02 ± 0.02	$F(1, 8) = 0.03$, $p = 86$, $\eta_p^2 = 0.04$	$F(1.8, 14.7) = 1.79$, $p < 0.2$, $\eta_p^2 = 0.18$	$F(1.99, 15.89) = 1.44$, $p = 0.27$, $\eta_p^2 = 0.15$

Bold values indicate significant main effects of the rmANOVA ($p < 0.05$)

Values are means ± SD. The main effects in regard to anticipation, drop height and interaction effects between anticipation and drop height are displayed with corresponding F values and p values (*$p < 0.05$; **$p < 0.001$), as well as effect sizes according to η_p^2 partial eta-squared

controlled according to the Benjamini–Hochberg–Yekutieli method.

To establish the interrelationship between neuromuscular control and mechanical regulators, bivariate two-tailed Pearson's correlations were calculated for the antigravity muscles m. vastus lateralis/medialis and leg stiffness. Furthermore, to recognise the effect of proactive neuromuscular adjustments correlations between antigravity muscles preactivity and loading forces have been measured.

Group data are presented as means ± standard deviations (SD).

Results

Relative (%) changes are detailed throughout this section and specific values for each measure can also be found within corresponding tables or figures. No drop jumps in the known conditions were excluded based on mentioned exclusion criteria in the experimental process section.

Leg stiffness and loading forces

Leg stiffness and loading forces (F_{max}/BW) are illustrated in Fig. 2, and grand means are displayed in Table 1. The rmANOVA revealed a significant main effect of anticipation for both parameters that amounted to 28% and 15%, respectively. Significant main effects of drop height were also reached for both parameters that amounted up to 43% and 32%, respectively. Effect size η_p^2 for changes in response to anticipation and drop height were large according to Cohen.

Leg stiffness was significantly reduced in the cheat condition compared to the known condition, and in the unknown condition compared to the known condition.

Joint kinematics: ankle, knee and hip

Anticipation-induced changes in ankle, knee and hip joint kinematics are illustrated in Table 2. At initial touchdown and during GC, the rmANOVA revealed a significant main effect of anticipation in all joints measured. Results of the unknown condition indicate an increased plantar flexion, knee and hip extension at touchdown, followed by an increased angular excursion in hip and knee joints during GC. The rmANOVA for the peak angular velocities during the eccentric phase indicates a significant main effect of anticipation for knee flexion velocities. The results revealed increased knee flexion velocities for the unknown vs. known conditions (17%).

The results of the cheat condition indicate increased knee flexion and plantar flexion at touchdown. Statistically, significant differences demonstrate a larger knee and hip angular excursion during GC between the cheat and known conditions. The results for hip and knee flexion velocities during the eccentric phase are significantly greater in the cheat than in the known condition (43% and 25%, respectively) ($p < 0.05$).

Electromyographic activity: shank and thigh musculature

The effect of anticipation on the neuromuscular control of the shank and thigh musculature is illustrated in Fig. 3. Grand means are displayed in Table 3 for the shank musculature and Table 4 for the thigh musculature. For all muscles and all phases, a significant main effect of anticipation was detected in the rmANOVA, and moderate to strong effect sizes were measured according to Cohen, except for RF MLR and LLR. The changes indicate an overall reduced EMG activity (2–25%) in the unknown compared to the

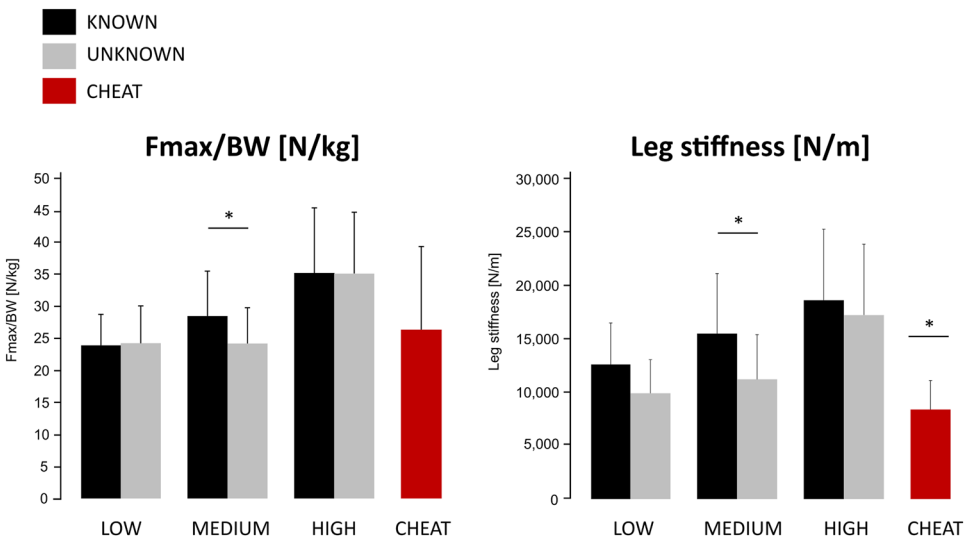

Fig. 2 The graphs indicate differences in loading forces (F_{max}/BW [N/kg]) and leg stiffness (N/m) between the unknown, known and cheat conditions in respect to the drop heights (low, medium and high). The dark columns display the results of the known condition. The light grey columns show the results of the unknown condition and the red columns that of the cheat condition. Significant results are marked with an asterisk (*$p < 0.05$)

Table 2 The effect of anticipation on drop jumps: joint angles at the event of touchdown (top), joint maximal angular excursions during GC (middle) and peak angular velocities during the eccentric phase (bottom) for the hip, knee and ankle joints

Parameter	Low			Medium		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction effect (A x Dh)
Joint angles at initial GC (°)										
Hip joint	157.1 ± 8.9	159.1 ± 8.3	157.4 ± 8.5	156.8 ± 8.3	157.9 ± 8.4	156.1 ± 8.5	157.4 ± 8.1	**$F(1, 17) = 20.99$, $p < 0.001$, $\eta_p^2 = 0.55$**	**$F(1.3, 22.6) = 4.28$, $p = 0.04$, $\eta_p^2 = 0.20$**	$F(2, 34) = 1.27$, $p = 0.29$, $\eta_p^2 = 0.07$
Knee joint	162.6 ± 6.4	167.9 ± 4.3*	167.8 ± 6.6	157.6 ± 4.0	161.5 ± 4.2*	154.8 ± 3.8	156.0 ± 4.2	**$F(1, 17) = 73.51$, $p < 0.001$, $\eta_p^2 = 0.81$**	**$F(1.2, 20) = 135.93$, $p < 0.001$, $\eta_p^2 = 0.89$**	**$F(1.4, 24.6) = 12.44$, $p = 0.001$, $\eta_p^2 = 0.42$**
Ankle joint	135.4 ± 5.5	137.7 ± 4.8	138.0 ± 6.7	135.1 ± 4.7	136.6 ± 4.3	135.9 ± 4.6	136.5 ± 4.2	**$F(1, 17) = 17.99$, $p = 0.001$, $\eta_p^2 = 0.51$**	$F(1.1, 18.9) = 0.58$, $p = 0.47$, $\eta_p^2 = 0.03$	**$F(2, 34) = 4.36$, $p = 0.02$, $\eta_p^2 = 0.20$**
Maximal angular excursions during GC (Δ°)										
Hip angle	21.5 ± 6.4	23.2 ± 6.6	27.2 ± 8.4*	20.5 ± 6.3	22.7 ± 6.7	21.0 ± 6.2	20.2 ± 6.3	**$F(1, 17) = 8.88$, $p = 0.01$, $\eta^2 = 0.34$**	**$F(1.2, 20.0) = 4.45$, $p = 0.04$, $\eta^2 = 0.21$**	**$F(2, 34) = 12.0$, $p < 0.001$, $\eta^2 = 0.41$**
Knee angle	46.6 ± 5.7	50.6 ± 5.9	55.7 ± 7.6*	45.0 ± 6.1	50.6 ± 6.3*	45.9 ± 8.3	45.4 ± 7.2	**$F(1, 17) = 21.52$, $p < 0.001$, $\eta^2 = 0.56$**	**$F(1.3, 21.8) = 6.76$, $p = 0.01$, $\eta^2 = 0.28$**	**$F(2, 34) = 22.28$, $p < 0.001$, $\eta^2 = 0.57$**
Ankle angle	48.5 ± 6.7	48.1 ± 6.9	48.0 ± 12.8	49.8 ± 5.5	48.9 ± 6.4	51.1 ± 6.9	50.0 ± 5.8	**$F(1, 17) = 9.25$, $p = 0.007$, $\eta_p^2 = 0.35$**	**$F(2, 34) = 7.29$, $p = 0.002$, $\eta_p^2 = 0.30$**	$F(2, 34) = 0.30$, $p = 0.74$, $\eta_p^2 = 0.02$
Peak angular velocity during eccentric phase (°/s)										
Hip flexion	19.2 ± 0.1	25.7 ± 8.5	33.8 ± 14.4*	20.1 ± 6.7	23.7 ± 6.6*	24.7 ± 8.5	25 ± 8.5	$F(1, 17) = 1.11$, $p = 0.31$, $\eta_p^2 = 0.06$	**$F(2, 34) = 3.92$, $p = 0.03$, $\eta_p^2 = 0.19$**	$F(1.4, 24) = 0.28$, $p = 0.68$, $\eta_p^2 = 0.02$
Knee flexion	48.6 ± 7.7	58.2 ± 9.3*	65.2 ± 15.4*	42.9 ± 6.2	51.8 ± 6.5*	43.9 ± 8.9	44.9 ± 8.1	**$F(1, 17) = 5.49$, $p = 0.03$, $\eta_p^2 = 0.24$**	**$F(2, 34) = 3.68$, $p = 0.04$, $\eta_p^2 = 0.18$**	$F(2, 34) = 2.078$, $p = 0.14$, $\eta_p^2 = 0.11$
Ankle plantar flexion	72.1 ± 5.0	75.7 ± 4.5	74.5 ± 12.8	80.0 ± 6.3	81.1 ± 5.6	91.0 ± 7.6	92.4 ± 6.6*	$F(1, 17) = 0.354$, $p = 0.56$, $\eta_p^2 = 0.02$	**$F(1.4, 23.8) = 17.55$, $p < 0.001$, $\eta_p^2 = 0.51$**	$F(1.3, 23.3) = 0.26$, $p = 0.69$, $\eta_p^2 = 0.02$

Bold values indicate significant main effects of the rmANOVA ($p < 0.05$)

Values are means ± SD. The main effects in regard to anticipation, drop height and interaction effects between anticipation and drop height are displayed with corresponding F values and p values (*$p < 0.05$), as well as effect sizes according to η_p^2 partial eta-squared

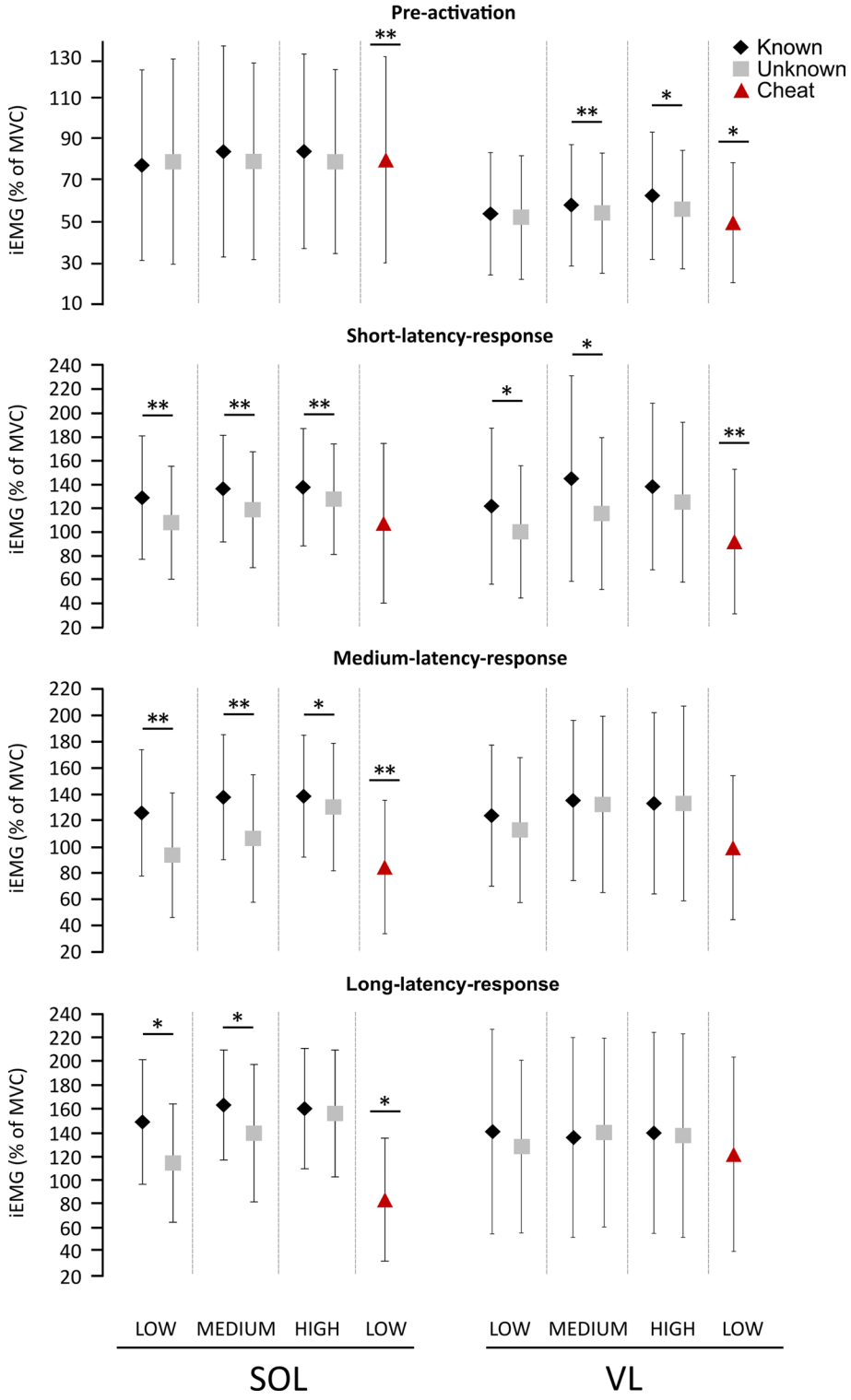

Fig. 3 Changes in grand means [% of maximum voluntary contraction (MVC)] in m. soleus (SOL) and m. vastus lateralis (VL), expressed as differences between the known, unknown and cheat conditions in respect to drop heights (low, medium and high). The dark triangles display the grand means with standard deviations of the known condition. The grey squares display the grand means of the unknown condition and the red triangles the grand means of the cheat condition. From top to bottom, the graphs demonstrate the results for the PRE, SLR, MLR and LLR phases. Significant results are marked with an asterisk (*$p < 0.05$; **$p < 0.001$)

known condition, except for VL LLR, Gmax SLR and LLR. Moreover, for GL, TA, VM, VL, RF, BF and Gmax a significant main effect of drop height was detected during PRE and SLR phases in the rmANOVA.

The cheat condition, in comparison to the known condition, displayed significantly greater muscle activity (3–9%) in SOL and VM and reduced muscle activity (9–20%) in TA, BF and VL in PRE. For the SLR phase, the muscles GL, TA, VM, VL and RF exhibited significantly ($p < 0.05$) reduced neuromuscular activity. During MLR, the muscles GL, VM and Gmax exhibited significantly reduced ($p < 0.05$) neuromuscular activity, whereas TA and SOL

Table 3 Changes in electromyographic activity in shank musculature regarding anticipation in the relevant phases: PRE (− 150 to 0 ms) and the reflex phases after GC with SLR (30–60 ms), MLR (60–85 ms) and LLR (85–120 ms)

Shank musculature	Low			Middle		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction (A × Dh)
GL										
PRE	0.79 ± 0.66	0.76 ± 0.67**	0.87 ± 0.73	0.85 ± 0.66	0.81 ± 0.66*	0.88 ± .65	0.82 ± 0.62	**$F(1, 21) = 9.34$, $p = 0.006$, $\eta_p^2 = 0.31$**	**$F(1.4, 30.4) = 10.69$, $p = 0.001$, $\eta_p^2 = 0.34$**	**$F(2, 42) = 0.58$, $p = 0.49$, $\eta_p^2 = 0.03$**
SLR	1.21 ± 0.69	1.05 ± 0.67**	1.00 ± 0.78**	1.27 ± 0.80	1.14 ± 0.68*	1.34 ± 0.93	1.29 ± 0.92	**$F(1, 21) = 22.45$, $p < 0.001$, $\eta_p^2 = 0.52$**	**$F(1.1, 22.8) = 7.41$, $p = 0.011$, $\eta_p^2 = 0.26$**	$F(2, 42) = 2.39$, $p = 0.10$, $\eta_p^2 = 0.10$
MLR	1.19 ± 0.76	0.93 ± 0.67**	0.81 ± 0.68**	1.32 ± 0.79	1.05 ± 0.67**	1.34 ± 0.98	1.20 ± 0.88*	**$F(1, 21) = 35.28$, $p < 0.001$, $\eta_p^2 = 0.63$**	**$F(1.3, 27.7) = 7.24$, $p = 0.007$, $\eta_p^2 = 0.26$**	**$F(1.5, 31.2) = 4.05$, $p = 0.04$, $\eta_p^2 = 0.16$**
LLR	1.42 ± 0.90	1.07 ± 0.71*	0.82 ± 0.57*	1.63 ± 1.20	1.30 ± 0.95*	1.54 ± 1.01	1.47 ± 1.03	**$F(1, 21) = 22.26$, $p < 0.001$, $\eta_p^2 = 0.52$**	**$F(1.6, 32.9) = 10.34$, $p = 0.001$, $\eta_p^2 = 0.33$**	**$F(2, 42) = 4.77$, $p = 0.01$, $\eta_p^2 = 0.19$**
TA										
PRE	0.44 ± 0.12	0.41 ± 0.13**	0.35 ± 0.16**	0.47 ± 0.13	0.46 ± 0.13*	0.51 ± 0.14	0.51 ± 0.14	**$F(1, 21) = 21.45$, $p < 0.001$, $\eta_p^2 = 0.51$**	**$F(1.4, 29.4) = 68.7$, $p < 0.001$, $\eta_p^2 = 0.77$**	**$F(2, 42) = 8.04$, $p = 0.001$, $\eta_p^2 = 0.28$**
SLR	0.51 ± 0.17	0.55 ± 0.16*	0.5 ± 0.19	0.46 ± 0.19	0.52 ± 0.20	0.45 ± 0.19	0.47 ± 0.19	**$F(1, 21) = 19.13$, $p < 0.001$, $\eta_p^2 = 0.48$**	**$F(1.4, 3.3) = 8.15$, $p = 0.004$, $\eta_p^2 = 0.28$**	$F(2, 42) = 1.67$, $p = 0.20$, $\eta_p^2 = 0.07$
MLR	0.53 ± 0.24	0.68 ± 0.26**	0.80 ± 0.40**	0.46 ± 0.22	0.55 ± 0.23*	0.47 ± 0.22	0.47 ± 0.22	**$F(1, 21) = 14.1$, $p = 0.001$, $\eta_p^2 = 0.40$**	**$F(1.2, 25.4) = 15.39$, $p < 0.001$, $\eta_p^2 = 0.42$**	**$F(2, 42) = 11.56$, $p < 0.001$, $\eta_p^2 = 0.36$**
LLR	0.47 ± 0.15	0.59 ± 0.21*	0.66 ± 0.25*	0.43 ± 0.13	0.52 ± 0.20*	0.44 ± 0.15	0.46 ± 0.17	**$F(1, 21) = 10.906$, $p = 0.003$, $\eta_p^2 = 0.342$**	**$F(1.5, 31.1) = 7.0$, $p = 0.006$, $\eta_p^2 = 0.25$**	**$F(2, 42) = 6.68$, $p = 0.003$, $\eta_p^2 = 0.24$**
SOL										
PRE	0.78 ± 0.47	0.79 ± 0.50	0.80 ± 0.50**	0.84 ± 0.52	0.80 ± 0.48	0.84 ± 0.48	0.79 ± 0.45	$F(1, 21) = 4.0$, $p = 0.06$, $\eta_p^2 = 0.16$	$F(2, 42) = 2.02$, $p = 0.14$, $\eta_p^2 = 0.09$	$F(1.0, 21.9) = 1.28$, $p = 0.27$, $\eta_p^2 = 0.06$
SLR	1.29 ± 0.52	1.08 ± 0.47**	1.08 ± 0.67	1.37 ± 0.45	1.19 ± 0.49**	1.38 ± 0.49	1.28 ± 0.46**	**$F(1, 21) = 25.09$, $p < 0.001$, $\eta_p^2 = 0.54$**	**$F(1.4, 30.2) = 9.06$, $p = 0.002$, $\eta_p^2 = 0.30$**	$F(2, 42) = 2.65$, $p = 0.08$, $\eta_p^2 = 0.11$
MLR	1.26 ± 0.48	0.94 ± 0.48**	1.38 ± 0.48**	1.38 ± 0.48	1.06 ± 0.49**	1.39 ± 0.47	1.30 ± 0.49*	**$F(1, 21) = 41.62$, $p < 0.001$, $\eta_p^2 = 0.67$**	**$F(1.5, 31.5) = 18.76$, $p < 0.001$, $\eta_p^2 = 0.47$**	**$F(2, 42) = 13.8$, $p < 0.001$, $\eta_p^2 = 0.4$**
LLR	1.5 ± 0.52	1.15 ± 0.50*	0.84 ± 0.52*	1.64 ± 0.46	1.40 ± 0.58*	1.61 ± 0.51	1.57 ± 0.53	**$F(1, 21) = 16.17$, $p = 0.001$, $\eta_p^2 = 0.44$**	**$F(1.2, 25.1) = 12.60$, $p = 0.001$, $\eta_p^2 = 0.38$**	**$F(2, 42) = 9.53$, $p < 0.001$, $\eta_p^2 = 0.31$**

Bold values indicate significant main effects of the rmANOVA ($p < 0.05$)

Values are normalised to iEMG, during MVC, time-normalised and expressed as means ± SD. The main effects in regard to anticipation, drop height and interaction effects between anticipation and drop height are displayed with corresponding F values and p values (*$p < 0.05$; **$p < 0.001$), as well as effect sizes according to η_p^2 partial eta-squared

Table 4 Changes in electromyographic activity in thigh musculature regarding anticipation in the relevant phases: PRE (− 150 to 0 ms) and the reflex phases after GC with SLR (30–60 ms), MLR (60–85 ms) and LLR (85–120 ms)

Thigh musculature	Low			Middle		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction (A × Dh)
VM										
PRE	0.57 ± 0.308	0.55 ± 0.311	0.63 ± 0.38*	0.61 ± 0.30	0.57 ± 0.30**	0.65 ± 0.32	0.59 ± 0.27	**$F(1, 21) = 9.08$, $p = 0.007$, $\eta_p^2 = 0.30$**	**$F(1.2, 25.6) = 14.4$, $p < 0.001$, $\eta_p^2 = 0.41$**	$F(1.1, 22.6) = 2.05$, $p = 0.17$, $\eta_p^2 = 0.09$
SLR	1.27 ± 0.509	1.00 ± 0.343**	0.84 ± 0.38**	1.39 ± 0.55	1.21 ± 0.45*	1.43 ± 0.69	1.38 ± 0.62	**$F(1, 21) = 13.8$, $p = 0.001$, $\eta_p^2 = 0.4$**	**$F(1.4, 23.3) = 6.59$, $p = 0.015$, $\eta_p^2 = 0.24$**	**$F(2, 42) = 9.13$, $p = 0.001$, $\eta_p^2 = 0.30$**
MLR	1.48 ± 0.531	1.22 ± 0.370**	1.15 ± 0.51*	1.61 ± 0.67	1.50 ± 0.64	1.53 ± 0.74	1.14 ± 0.65	**$F(1, 21) = 16.45$, $p = 0.001$, $\eta_p^2 = 0.44$**	**$F(2, 42) = 4.87$, $p = 0.01$, $\eta_p^2 = 0.19$**	$F(2, 42) = 1.97$, $p = 0.15$, $\eta_p^2 = 0.09$
LLR	1.55 ± 0.731	1.42 ± 0.559	1.31 ± 0.52	1.57 ± 0.84	1.50 ± 0.64	1.55 ± 0.87	1.52 ± 0.81	$F(1, 21) = 1.09$, $p = 0.31$, $\eta_p^2 = 0.05$	$F(1.6, 33.0) = 0.50$, $p = 0.61$, $\eta_p^2 = 0.02$	$F(2, 42) = 1.25$, $p = 0.30$, $\eta_p^2 = 0.06$
VL										
PRE	0.56 ± 0.314	0.54 ± 0.318	0.51 ± 0.31*	0.60 ± 0.31	0.56 ± 0.31**	0.65 ± 0.33	0.58 ± 0.30*	**$F(1, 21) = 17.1$, $p < 0.001$, $\eta_p^2 = 0.45$**	**$F(1.2, 24.7) = 16.13$, $p < 0.001$, $\eta_p^2 = 0.43$**	$F(1.1, 22.3) = 3.85$, $p = 0.06$, $\eta_p^2 = 0.16$
SLR	1.21 ± 0.655	1.00 ± 0.56*	0.92 ± 0.61**	1.45 ± 0.86	1.15 ± 0.64*	1.38 ± 0.7	1.25 ± 0.67	**$F(1, 21) = 11.53$, $p = 0.003$, $\eta_p^2 = 0.35$**	**$F(2, 42) = 10.63$, $p < 0.001$, $\eta_p^2 = 0.34$**	$F(1.4, 28.6) = 1.87$,$p = 0.17$, $\eta_p^2 = 0.08$
MLR	1.25 ± 0.538	1.14 ± 0.55	1.00 ± 0.55	1.36 ± 0.61	1.33 ± 0.67	1.34 ± 0.69	1.34 ± 0.74	$F(1, 21) = 2.3$, $p = 0.15$, $\eta_p^2 = 0.10$	$F(1.4, 28.2) = 2.9$, $p = 0.09$, $\eta_p^2 = 0.13$	**$F(2, 40) = 3.32$, $p = 0.05$, $\eta_p^2 = 0.14$**
LLR	1.42 ± 0.858	1.3 ± 0.73	1.23 ± 0.82	1.37 ± 0.84	1.42 ± 0.79	1.41 ± 0.84	1.39 ± 0.85	$F(1, 21) = 0.57$, $p = 0.46$, $\eta_p^2 = 0.03$	$F(1.2, 25.2) = 0.24$, $p = 0.67$, $\eta_p^2 = 0.01$	**$F(2, 42) = 4.64$, $p = 0.02$, $\eta_p^2 = 0.18$**
RF										
PRE	0.61 ± 0.529	0.61 ± 0.53	0.62 ± 0.53	0.64 ± 0.53	0.62 ± 0.53*	0.69 ± 0.55	0.64 ± 0.47	**$F(1, 21) = 6.77$, $p = 0.02$, $\eta_p^2 = 0.24$**	**$F(1.09, 22.8) = 4.2$, $p = 0.049$, $\eta_p^2 = 0.17$**	$F(1.1, 23.9) = 2.40$,$p = 0.13$, $\eta_p^2 = 0.10$
SLR	1.27 ± 0.785	1.04 ± 0.73**	0.91 ± 0.61**	1.45 ± 0.94	1.30 ± 0.84	1.44 ± 0.94	1.43 ± 1.00	**$F(1, 21) = 6.40$, $p = 0.02$, $\eta_p^2 = 0.23$**	**$F(1.9, 4.0) = 10.23$, $p = 0.002$, $\eta_p^2 = 0.33$**	**$F(2, 42) = 5.65$, $p = 0.007$, $\eta_p^2 = 0.21$**
MLR	2.14 ± 1.502	2.02 ± 1.20	2.05 ± 1.47	2.10 ± 1.68	2.12 ± 1.50	2.08 ± 1.61	2.10 ± 1.57	$F(1, 21) = 0.07$, $p = 0.80$, $\eta_p^2 = 0.003$	$F(1.5, 31.3) = 0.03$, $p = 0.94$, $\eta_p^2 = 0.001$	$F(2, 42) = 1.32$, $p = 0.28$, $\eta_p^2 = 0.06$
LLR	1.53 ± 1.073	1.45 ± 0.86	1.46 ± 1.05	1.50 ± 1.20	1.51 ± 1.07	1.48 ± 1.15	1.50 ± 1.12	$F(1, 21) = 0.07$, $p = 0.78$, $\eta_p^2 = 0.003$	$F(1.5, 31.3) = 0.03$, $p = 0.94$, $\eta_p^2 = 0.001$	$F(2, 42) = 1.31$, $p = 0.28$, $\eta_p^2 = 0.06$
BF										
PRE	0.33 ± 0.184	0.31 ± 0.19*	0.29 ± 0.17*	0.34 ± 0.20	0.33 ± 0.19*	0.34 ± 0.20	0.34 ± 0.20	**$F(1, 21) = 7.85$, $p = 0.01$, $\eta_p^2 = 0.27$**	**$F(1.1, 23.7) = 6.92$, $p = 0.01$, $\eta_p^2 = 0.25$**	**$F(2, 42) = 4.42$, $p = 0.02$, $\eta_p^2 = 0.17$**
SLR	0.39 ± 0.179	0.35 ± 0.19*	0.39 ± 0.24	0.40 ± 0.21	0.34 ± 0.13*	0.44 ± 0.20	0.43 ± 0.21	**$F(1, 21) = 12.2$, $p = 0.002$, $\eta_p^2 = 0.367$**	**$F(1.4, 29.5) = 11.24$, $p = 0.001$, $\eta_p^2 = 0.35$**	$F(2, 42) = 1.89$, $p = 0.16$, $\eta_p^2 = 0.08$
MLR	0.38 ± 0.187	0.37 ± 0.19	0.38 ± 0.25	0.40 ± 0.17	0.37 ± 0.18	0.45 ± 0.17	0.44 ± 0.21	$F(1, 21) = 2.28$, $p = 0.15$, $\eta_p^2 = 0.10$	**$F(1.3, 27.6) = 5.05$, $p = 0.02$, $\eta_p^2 = 0.19$**	$F(2, 42) = 0.36$, $p = 0.70$, $\eta_p^2 = 0.02$

Table 4 (continued)

Thigh musculature	Low			Middle		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction (A × Dh)
LLR	0.41 ± 0.213	0.36 ± 0.23	0.29 ± 0.15	0.48 ± 0.23	0.42 ± 0.22	0.49 ± 0.25	0.49 ± 0.27	$F(1, 21) = 4.03$, $p = 0.06$, $\eta_p^2 = 0.16$	**$F(1.6, 33.2) = 18.13$, $p < 0.001$, $\eta_p^2 = 0.46$**	$F(2, 42) = 2.83$, $p = 0.07$, $\eta_p^2 = 0.12$
Gmax										
PRE	0.49 ± 0.335	0.49 ± 0.35	0.48 ± 0.35	0.53 ± 0.39	0.49 ± 0.35	0.52 ± 0.36	0.52 ± 0.35	$F(1, 21) = 3.44$, $p = 0.08$, $\eta_p^2 = 0.14$	**$F(1.2, 24.3) = 3.2$, $p = 0.08$, $\eta_p^2 = 0.13$**	**$F(1.1, 22.9) = 1.62$, $p = 0.22$, $\eta_p^2 = 0.07$**
SLR	0.77 ± 0.363	0.64 ± 0.43	0.58 ± 0.33	0.88 ± 0.62	0.74 ± 0.45	0.80 ± 0.34	0.86 ± 0.66	$F(1, 21) = 3.5$, $p = 0.08$, $\eta_p^2 = 0.14$	**$F(2, 42) = 5.6$, $p = 0.007$, $\eta_p^2 = 0.21$**	$F(1.1, 22.8) = 1.83$, $p = 0.19$, $\eta_p^2 = 0.08$
MLR	0.98 ± 0.58	0.84 ± 0.58**	0.74 ± 0.51**	1.08 ± 0.68	0.94 ± 0.72**	1.02 ± 0.50	1.00 ± 0.69	**$F(1, 21) = 9.05$, $p = 0.007$, $\eta_p^2 = 0.30$**	**$F(2, 42) = 1.88$, $p = 0.03$, $\eta_p^2 = 0.16$**	$F(1.3, 27.7) = 3.17$, $p = 0.08$, $\eta_p^2 = 0.13$
LLR	0.84 ± 0.42	0.77 ± 0.33	0.72 ± 41	0.90 ± 0.43	0.85 ± 0.36	0.92 ± 0.43	0.96 ± 0.36	$F(1, 21) = 0.3$, $p = 0.59$, $\eta_p^2 = 0.01$	**$F(2, 42) = 15.81$, $p < 0.001$, $\eta_p^2 = 0.43$**	$F(2, 42) = 2.95$, $p = 0.06$, $\eta_p^2 = 0.12$

Bold values indicate significant main effects of the rmANOVA ($p < 0.05$)

Values are normalised to iEMG, during MVC, time-normalised and expressed as means ± SD. The main effects in regard to anticipation, drop height and interaction effects between anticipation and drop height are displayed with corresponding F values and p values (*$p < 0.05$; **$p < 0.001$), as well as effect sizes according to η_p^2 partial eta-squared

displayed significantly ($p < 0.05$) increased neuromuscular activity compared to the known condition. In the LLR phase, GL and TA displayed significantly reduced neuromuscular activity in the cheat condition ($p < 0.05$).

Antagonistic co-activation

Changes in antagonistic co-activation referring to TA/SOL and BF/RF are illustrated in Fig. 4 and Table 5. In the unknown condition, TA/SOL was significantly greater compared to the known condition for the SLR, MLR and LLR phases, indicated by a significant main effect of anticipation from 7% as measured for the MLR high condition and up to 45% in the LLR low condition. Moreover, the rmANOVA revealed a significant main effect for drop height for TA/SOL which indicates greater reductions in the unknown vs. known in TA/SOL activation levels when comparing low drop heights with high drop heights as well as increased co-activation levels for BF/RF during MLR and LLR. BF/RF was reduced in the unknown vs. known condition for the MLR and LLR phases by 4% during the MLR low condition and up to 22% in the MLR and LLR medium condition, as manifested by medium and strong effect sizes according to Cohen.

For TA/SOL and BF/RF, the cheat condition revealed a significant difference ($p < 0.05$) from the known condition, except for BF/RF MLR.

Correlations

Differences between known and unknown conditions for the parameter leg stiffness were positively correlated to the differences calculated for VL PRE and LLR ($r = 0.49$, $p < 0.05$), Gmax SLR ($r = 0.5$, $p < 0.05$) and VM MLR iEMG (Fig. 5). Furthermore, differences between the known and unknown conditions for VM PRE were positively correlated to differences in F_{max}/BW ($r = 0.71$, $p < 0.01$).

Strong negative correlations were assessed between changes in leg stiffness and maximum knee excursion established between known, unknown and cheat conditions (Fig. 6). Lastly, strong positive correlations were assessed between the parameters leg stiffness and F_{max}/BW for known and unknown conditions (Fig. 6).

Discussion

The present study concentrated on analysing the effects of anticipation on leg stiffness modulation during fast reactive movements by providing either known, unknown or cheated drop heights (Fig. 1). The findings demonstrate that leg stiffness accompanied by EMG activities of the antigravity decreased, while angular excursions and antagonistic

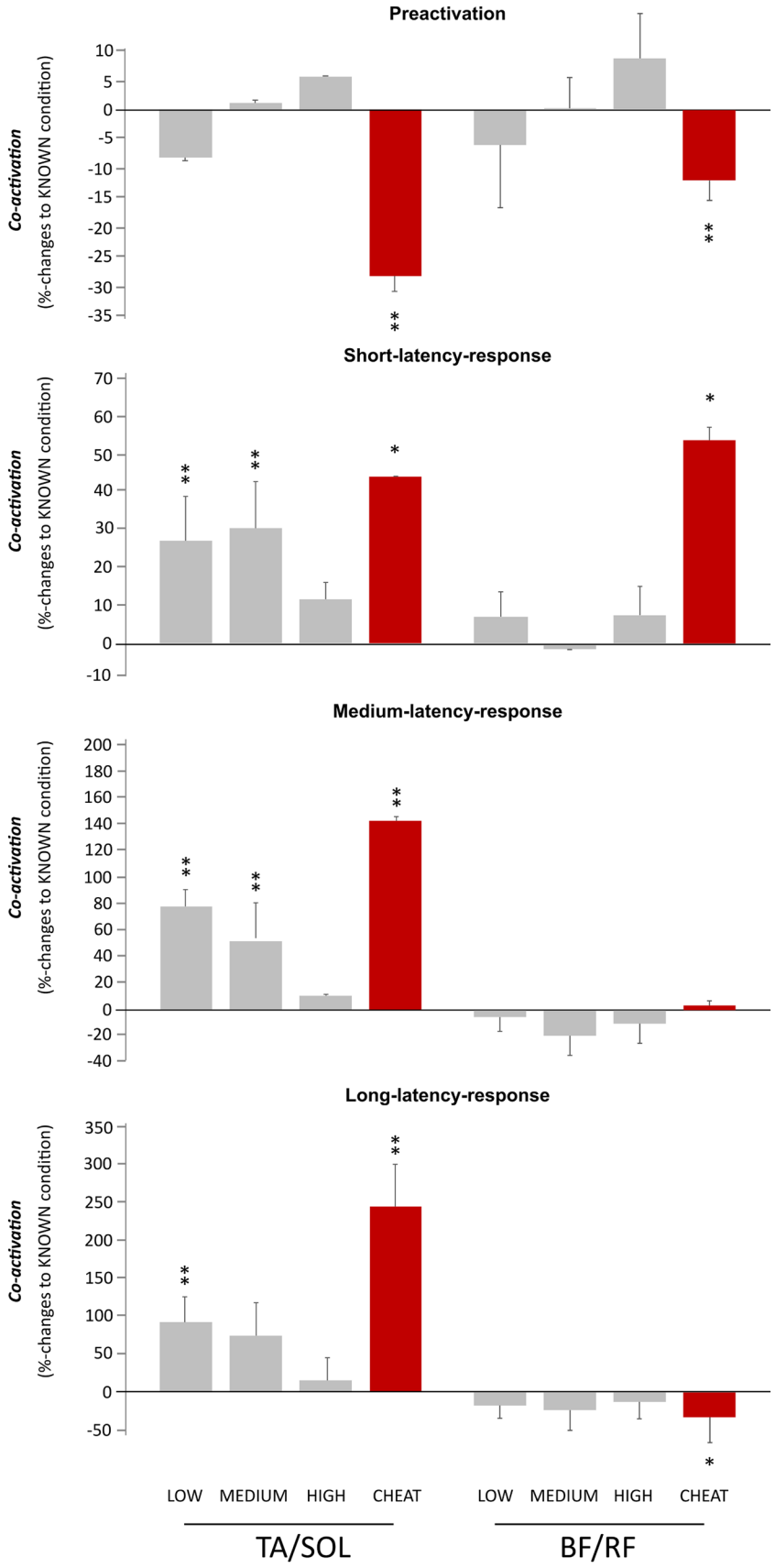

Fig. 4 Percentile changes in antagonistic co-activation in the shank and thigh musculature, expressed as differences between unknown (grey bars) and cheat (red bars) condition to the known condition for TA/SOL and BF/RF, respectively, for low, medium and high drop height conditions. From top to bottom, the graphs demonstrate the results for the PRE, SLR, MLR and LLR phases. The bars represent the grand means with their standard deviations. Significant results are marked with an asterisk (*$p < 0.05$; **$p < 0.001$)

Table 5 Raw data on co-activation ratios in the shank and thigh musculature in regard to anticipation during the relevant phases: PRE, SLR, MLR and LLR. Values are normalised to iEMG during MVC and expressed as means ± SD in percentile

	Low			Middle		High		Statistics: rmANOVA (p, F, η_p^2)		
	Known	Unknown	Cheat	Known	Unknown	Known	Unknown	Main effect anticipation (A)	Main effect drop height (Dh)	Interaction effect (A × Dh)
TA/SOL										
PRE	0.72 ± 0.32	0.67 ± 0.3	0.52 ± 0.24**	0.72 ± 0.33	0.73 ± 0.33	0.73 ± 0.29	0.77 ± 0.3	$F(1, 21) = 0.05$, $p = 0.83$, $\eta_p^2 = 0.002$	$F(1.3, 27.2) = 3.73$, $p = 0.05$, $\eta_p^2 = 0.15$	**$F(2, 42) = 7.06$, $p = 0.002$, $\eta_p^2 = 0.25$**
SLR	0.45 ± 0.21	57 ± 0.21**	0.64 ± 0.31*	0.36 ± 0.17	0.47 ± 0.17**	0.34 ± 0.16	0.38 ± 0.17	**$F(1, 21) = 37.44$, $p < 0.001$, $\eta_p^2 = 0.64$**	**$F(1.4, 28.4) = 16.22$, $p < 0.001$), $\eta_p^2 = 0.44$**	**$F(2, 42) = 4.67$, $p = 0.02$, $\eta_p^2 = 0.18$**
MLR	0.49 ± 0.35	0.88 ± 0.51**	1.19 ± 0.88**	0.4 ± 0.32	0.6 ± 0.33**	0.39 ± 0.3	0.43 ± 0.33	**$F(1, 21) = 20.04$, $p < 0.001$, $\eta_p^2 = 0.49$**	**$F(1.1, 23.1) = 11.45$, $p = 0.002$, $\eta_p^2 = 0.353$**	**$F(1.4, 29.7) = 16.06$, $p < 0.001$, $\eta_p^2 = 0.43$**
LLR	0.32 ± 0.09	0.61 ± 38**	1.1 ± 0.94**	0.27 ± 0.09	0. 47 ± 0.36	0.3 ± 0.17	0.35 ± 0.3	**$F(1, 21) = 9.87$, $p = 0.005$, $\eta_p^2 = 0.32$**	**$F(1.3, 27.8) = 8.07$, $p = 0.005$, $\eta_p^2 = 0.28$**	**$F(1.6, 33.2) = 9.75$, $p = 0.001$, $\eta_p^2 = 0.32$**
BF/RF										
PRE	0.77 ± 0.65	0.73 ± 0.69	0.68 ± 0.59**	0.75 ± 0.61	0.75 ± 0.65	0.69 ± 0.48	0.75 ± 0.58	$F(1, 21) = 0.04$, $p = 0.84$, $\eta_p^2 = 0.002$	$F(1.1, 23.7) = 0.51$, $p = 0.5$, $\eta_p^2 = 0.02$	**$F(1.2, 24.4) = 4.34$, $p = 0.04$, $\eta_p^2 = 0.17$**
SLR	0.41 ± 0.26	0.44 ± 0.23	0.63 ± 0.55*	0.36 ± 0.22	0.35 ± 0.19	0.41 ± 0.29	0.44 ± 0.42	$F(1, 21) = 1.29$, $p = 0.27$, $\eta_p^2 = 0.06$	$F(1.2, 25.3) = 1.69$, $p = 0.21$, $\eta_p^2 = 0.07$	$F(1.4, 28.9) = 0.32$, $p = 0.65$, $\eta_p^2 = 0.02$
MLR	0.23 ± 0.13	0.22 ± 0.11	0.24 ± 0.17	0.27 ± 0.19	0.22 ± 0.13	0.29 ± 0.17	0.26 ± 0.12	$F(1, 21) = 2.32$, $p = 0.14$, $\eta_p^2 = 0.10$	**$F(2, 42) = 5.37$, $p = 0.008$, $\eta_p^2 = 0.20$**	$F(2, 42) = 2.30$, $p = 0.113$, $\eta_p^2 = 0.10$
LLR	0.36 ± 0.33	0.30 ± 0.22	0.24 ± 0.14*	0.45 ± 0.44	0.35 ± 0.24	0.47 ± 0.39	0.41 ± 0.26	$F(1, 21) = 3.41$, $p = 0.08$, $\eta_p^2 = 0.14$	**$F(2, 42) = 12.89$, $p < 0.001$, $\eta_p^2 = 0.38$**	$F(2, 42) = 1.87$, $p = 0.17$, $\eta_p^2 = 0.08$

Bold values indicate significant main effects of the rmANOVA ($p < 0.05$)

The main effects regarding anticipation, drop height and interaction effects between anticipation and drop height are also shown with corresponding F values and p values (*$p < 0.05$; **$p < 0.001$), as well as effect sizes according to η_p^2 partial eta-squared

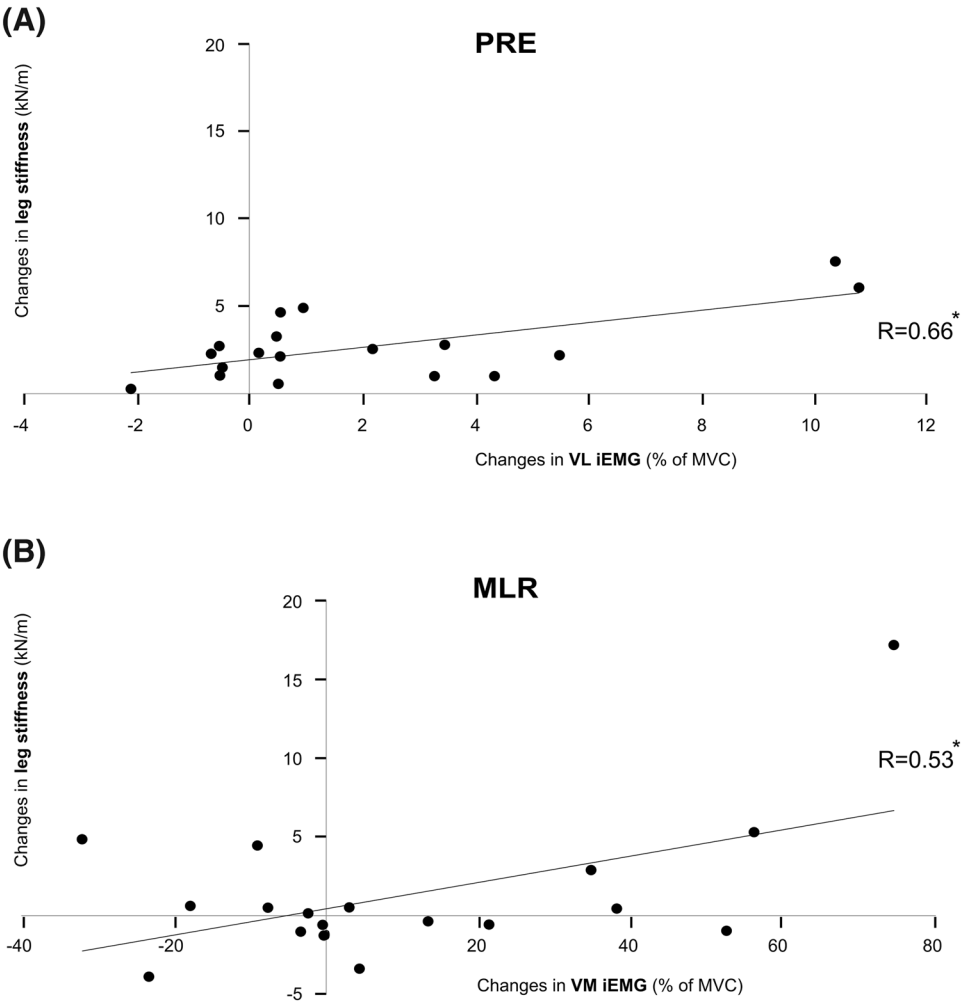

Fig. 5 Bivariate correlations and correlation coefficients among variables **a** VL and leg stiffness during PRE for low drop height and **b** VM and leg stiffness during MLR for high drop height. The black circles display the grand means of the changes from the known to unknown condition. Significant results are marked with an asterisk (*$p < 0.05$)

co-activations progressively increased from known to unknown to cheat conditions (Tables 1, 2, 3, 4, Fig. 1). The biomechanical findings correlate with electromyographic adaptations, which were determined by activation intensities before and after touchdown. The study's results show that anticipation systematically influences the neuromechanical coupling in the SSC modulation of shank and thigh muscle activity, which in turn effects joint configurations and overall leg stiffness adaptations.

To interpret these findings, this paper will first focus on proactive modulations and second on reactive modulations after touchdown.

Proactive modulations are related to changes in leg stiffness

Leg stiffness was found to be a key determinant for fast reactive movement performance aiming to achieve significant jump heights coupled with peak forces (Arampatzis et al. 2001b; Blum et al. 2009; Farley et al. 1998; Ferris and Farley 1997; Gollhofer and Kyröläinen 1991; Kuitunen et al. 2007; Oliver and Smith 2010). Leg extensor activity during preactivation was found to be positively correlated to leg stiffness (Fig. 5). Reduced muscle activation in the antigravity muscles (Ritzmann et al. 2016) as is the case in the unknown as compared to the known condition is, therefore, related to a reduced amount of leg stiffness (up to 28% in the unknown condition; up to 33% in the cheat condition) and hence may have negatively affected the SSC performance, as indicated by the reduction in force and jump height (Gollhofer and Kyröläinen 1991). This is true not only for the leg muscles' activation intensities counteracting gravity during the GC, but also valid for the neuromuscular activation prior to touchdown; the outcomes manifested that the preactivation of the leg extensors is positively correlated to the loading forces (Fig. 5). In view of recent articles (Arampatzis et al. 2001b; Farley et al. 1998; Ferris and Farley 1997; Gollhofer and Kyröläinen 1991), it can be supposed that individuals with a higher neuromuscular activation in the unknown or cheat conditions can profit from a reinforcing of muscular stiffness to oppose large impact forces right after GC.

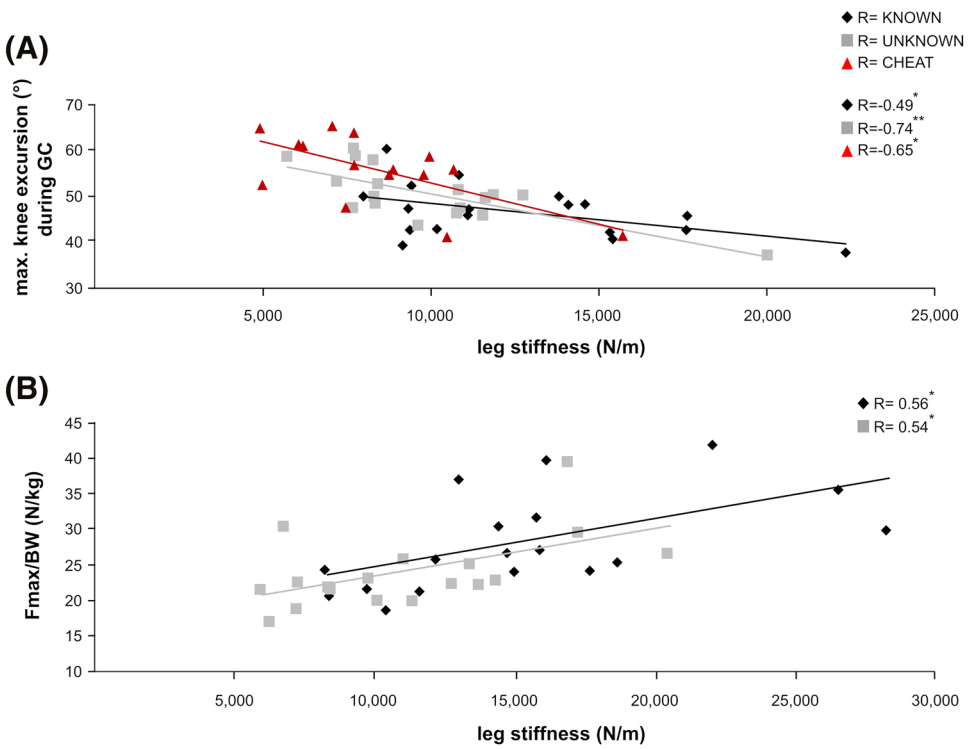

Fig. 6 Bivariate correlations and correlation coefficients among the variables leg stiffness with knee excursion and loading force (F_{max}/BW). The black triangles display the grand means of the known condition, the grey squares that of the unknown condition and the red triangles display the grand means of the cheat condition. The top graph **a** shows the results for the low drop height condition and the bottom graph **b** that of the medium drop height condition. Significant results are marked with an asterisk (*$p < 0.05$)

To execute a fast reactive movement, a preactivated musculature is the determining factor to be able to store elastic energy in the tendomuscular system that can be reutilised later on during the push-off phase (Komi 2003; Komi and Gollhofer 1997; Leukel et al. 2009; Leukel et al. 2012). Recoil of elastic energy cannot be expected if the preprogramming does not prepare the tendomuscular system prior to GC (Gollhofer and Kyröläinen 1991; Komi 2003; Komi and Gollhofer 1997; Kramer et al. 2012; Lesinski et al. 2016; Leukel et al. 2009). Furthermore, preactivation modulation seems also to be dependent upon varying environmental conditions, such as different drop heights, ground stiffness or varying gravity conditions (Arampatzis et al. 2004; Gollhofer and Kyröläinen 1991; Lesinski et al. 2016; Ritzmann et al. 2016; Sousa et al. 2007). Prior studies have shown that the central nervous system (CNS) is able to adapt itself remarkably well to a foreseen environmental condition, as it benefits from being nourished by sensory information arising from the visual and vestibular systems (McDonagh and Duncan 2002; Miall and Wolpert 1996), leading to fine-tuned motor actions in the compensatory phase resulting in an enhanced performance (Komi 2003; Taube et al. 2012b). When anticipation is missing or false information about an upcoming situation is provided, as indicated in this study, neuromuscular drive prior to GC is markedly reduced in the unknown condition in VL, as compared to the known condition, by approximately 11%, and by 9% for the cheat condition (Tables 2, 3). Prior studies have also revealed comparable results, in that neuromuscular drive was downregulated when subjects were confronted with variability in impact loads (Ritzmann et al. 2016) induced by altered gravity or variability in landing tasks (Leukel et al. 2012).

The current study shows that the CNS is either not capable of providing adequate neuromuscular activity, and hence leg stiffness, to fit the requirements of the loading condition in the unknown or the cheat conditions. The reason might arise from the lack of anticipation during the condition, which prevents the CNS from building an adequate motor program for the preactivation phase (Leukel et al. 2012; Taube et al. 2012a). It is also very likely that subjects adopted a more conservative motor strategy which may be as a means to limit the risk of potential injury (i.e. increasing leg compliance and reducing joint stiffness when insufficient information is provided to plan an optimal motor strategy). The neuromuscular activation in the unknown condition was therefore drastically dampened compared to being exposed to greater expected stretch loads, and reactive movement capability was estimated to be reduced (Taube et al. 2012b). Contextually, prior studies that analysed neuromuscular activation patterns in subjects performing jumps from excessive heights (> 75 cm) have shown that a protective strategy had been adapted by inhibiting neuromuscular drive through supraspinal control during the preactivity phase to prevent injuries of the MTU from occurring (Ishikawa and Komi 2004; Komi and Gollhofer 1997; Leukel et al. 2009; Taube et al. 2012b). Consequently, it can be speculated that this is also true for situations involving uncertainty, as was the case for the unknown falling heights.

Reactive modulations associated with leg stiffness

Neuromuscular activations were reduced during the GC phase for nearly all muscles in the unknown condition (up to 25%) as well as in the cheat condition (up to 44%) (Tables 2, 3). Analysing the EMG activity of the co-activations of antagonistic muscles in TA/SOL and BF/RF reveals that they were increased through the reactive phases for both the unknown (up to 45%) and cheat conditions (up to 68%) (Table 5, Fig. 4). Based on the literature, an increased co-activation of antagonistic muscles is adopted when joint stabilisation is required to guarantee a protection of the musculoskeletal structure (Aagaard et al. 2000; Arai et al. 2013; Behm et al. 2010; Lesinski et al. 2016; van Dieen et al. 2003). The negative effect of this, however, is the deceleration of SSC performance by enhancing resistance in the movement direction, which reduces jump height (Behm et al. 2010; Lesinski et al. 2016).

Another aspect deals with the modulation of leg stiffness by anticipation, manifested by correlations between leg stiffness and the inhibited neuromuscular activation of the plantar flexors and knee extensors when jumps were performed in unknown or cheat conditions. Both muscle groups are antigravity muscles that are greatly involved in the stabilisation of joints or other body parts by opposing the effects of the gravitational pull (Horita et al. 2002; Kellis et al. 2003; Viitasalo et al. 1998). As manifested by the correlations between the diminished activation intensities, the resulting increase in joint deflections and the reduction in leg stiffness, the neuromechanical coupling and efficiency of the SSC are highly dependent on anticipation. According to the spring-mass model, leg function within the class of reactive movements is advantageous when the falling height is correctly predicted, but massively restricted in the unknown and cheat conditions. A reduced leg stiffness is detrimental for providing a fast reactive movement, leading to longer GCT, lower jump performance and lower rate of force developments in unknown and cheat conditions (Arampatzis et al. 2001a; Gollhofer and Kyröläinen 1991).

Moreover, anticipation also modulates the ability of the system to generate larger peak forces, manifested by positive correlations between VM PRE and loading forces (Fig. 6). Due to a reduced neuromuscular drive in the unknown and cheat conditions, the tendomuscular system is incapable of generating higher peak forces. The strategy of the CNS seems to be to dampen the unexpected impact loads through increased knee flexions, as manifested by the strong negative correlations between leg stiffness and knee excursion (Fig. 6). Our results also accord with prior studies by Arampatzis et al. (2001b) and Farley et al. (1998), who have suggested that body geometry affects leg stiffness and knee angle upon contact. Increased knee joint excursions during GC in the unknown and cheat conditions may have led to the inability to maintain leg stiffness (Fig. 6). The cheat condition even shows a 20% increase in knee excursion (Table 1), leading to a longer GCT and an inability to perform a reactive movement and instead performing a counter movement jump (Gollhofer et al. 1992; Jidovtseff et al. 2014).

Practical considerations

The aspect of uncertainty could be incorporated into existing training programs that have been working on improving lower limb muscular preactivation in athletes to increase lower extremity stiffness through plyometric exercises (Kyrölänen et al. 1991). This might provide an opportunity to accustom athletes to variable environments, which need to be adapted to the specific activity demands of particular sports (jumping, running, hopping, change of direction) with the aim of improving performance. However, more research needs to go into understanding injury risk developments since both excessive and insufficient lower limb stiffness are associated with injury risks (Butler et al. 2003; Flanagan et al. 2008).

Limitation

For a conclusive statement, it is crucial to consider the limitations of this experiment. Two aspects are of importance; the first deals with the jump criteria, and the second with the methodological EMG approach. For the known condition, the movement task has been standardised according to the literature (Bobbert et al. 1987a, b; Gollhofer et al. 1992; Gollhofer and Kyröläinen 1991; Komi 2003; Komi and Gollhofer 1997) with the jumps being performed stiff and reactive with short GCTs. Trials with attributes beyond certain limits have been excluded and this selection—although evidence based—may have biased the results. EMG recordings have been made in highly dynamic movements and thus, we cannot exclude a systematic noise due to the electrode moment above the activated muscle belly. However, as the test paradigm was always the same jump with identical dropping heights, we would expect that this interreference would be systematic and would not influence the results of the study.

Conclusion and perspective

In conclusion, this study shows that anticipation affects leg stiffness through modulation of the antigravity musculature's preactivity rate (Ritzmann et al. 2016). When exposed to unknown drop height conditions, neuromuscular activity seems to be inhibited, possibly through supraspinal inhibition (Leukel et al. 2009; Taube et al. 2008, 2012a, b), influencing reactive neuromuscular, kinematic and force outputs.

The unknown condition displays reduced neuromuscular activity, enhanced joint deflections in knee and hip during ground contact and augmented loading forces. In scenarios where humans are provided with false information about the loading condition, dramatically reduced leg stiffnesses and increased angular excursions in the ankle, knee and hip occur, leading to an inability to perform fast reactive movements. The central nervous system's strategy seems to be overall protective in nature; reducing neuromuscular preactivity and increasing antagonistic muscular activations during GC cause leg stiffness to be reduced, possibly to dampen higher loading forces.

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Author contributions MH designed and conducted the experiment, collected and analysed the data and wrote the manuscript. KF designed the experiment, analysed data and edited manuscript. JW collected data, designed and conducted the experiment and analysed data. AB designed the experiment and edited manuscript. RR designed the experiment, analysed data and edited manuscript. All authors read and approved the manuscript.

Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest related to this study.

References

Aagaard P, Simonsen EB, Andersen JL, Magnusson SP, Bojsen-Moller F, Dyhre-Poulsen P (2000) Antagonist muscle coactivation during isokinetic knee extension. Scand J Med Sci Sports 10:58–67

Arai A, Ishikawa M, Ito A (2013) Agonist-antagonist muscle activation during drop jumps. Eur J Sport Sci 13:490–498

Arampatzis A, Bruggemann GP, Klapsing GM (2001a) Leg stiffness and mechanical energetic processes during jumping on a sprung surface. Med Sci Sports Exerc 33:923–931

Arampatzis A, Schade F, Walsh M, Brüggemann G-P (2001b) Influence of leg stiffness and its effect on myodynamic jumping performance. J Electromyogr Kinesiol 11:355–364

Arampatzis A, Stafilidis S, Morey-Klapsing G, Brüggemann GP (2004) Interaction of the human body and surfaces of different stiffness during drop jumps. Med Sci Sports Exerc 36:451–459

Behm DG, Drinkwater EJ, Willardson JM, Cowley PM (2010) Canadian society for exercise physiology position stand: the use of instability to train the core in athletic and nonathletic conditioning. Appl Physiol Nutr Metab 35:109–112

Benjamini Y, Hochberg Y (1995) Controlling the false discovery rate: a practical and powerful approach to multiple testing. J R Stat Soc Ser B (Methodological) 57:289–300

Benjamini Y, Yekutieli D (2005) Quantitative trait loci analysis using the false discovery rate. Genetics 171:783–790

Blum Y, Lipfert SW, Seyfarth A (2009) Effective leg stiffness in running. J Biomech 42:2400–2405

Bobbert MF, Huijing PA, van Ingen Schenau GJ (1987a) Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. Med Sci Sports Exerc 19:332–338

Bobbert MF, Huijing PA, van Ingen Schenau GJ (1987b) Drop jumping. II. The influence of dropping height on the biomechanics of drop jumping. Med Sci Sports Exerc 19:339–346

Brauner T, Sterzing T, Wulf M, Horstmann T (2014) Leg stiffness: comparison between unilateral and bilateral hopping tasks. Hum Mov Sci 33:263–272

Butler RJ, Crowell HP III, Davis IM (2003) Lower extremity stiffness: implications for performance and injury. Clin Biomech (Bristol, Avon) 18:511–517

Cohen J (1988) Statistical power analysis for the behavioral sciences, 2nd edn. Erlbaum, Hillsdale

Coleman DR, Cannavan D, Horne S, Blazevich AJ (2012) Leg stiffness in human running: comparison of estimates derived from previously published models to direct kinematic-kinetic measures. J Biomech 45:1987–1991

Erdfelder E, Faul F, Buchner A (1996) GPOWER: a general power analysis program. Behav Res Methods Instrum Comput 28:1–11

Farley CT, González O (1996) Leg stiffness and stride frequency in human running. J Biomech 29:181–186

Farley CT, Houdijk HH, van Strien C, Louie M (1998) Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. J Appl Physiol (Bethesda, Md.: 1985) 85:1044–1055

Ferris DP, Farley CT (1997) Interaction of leg stiffness and surfaces stiffness during human hopping. J Appl Physiol (Bethesda, Md.: 1985) 82:15–22 **(discussion 13-4)**

Flanagan EP, Galvin L, Harrison AJ (2008) Force production and reactive strength capabilities after anterior cruciate ligament reconstruction. J Athl Train 43:249–257

Fong SSM, Ng SSM, Guo X, Wang Y, Chung RCK, Stat G, Ki WY, Macfarlane DJ (2015) Deficits in lower limb muscle reflex contraction latency and peak force are associated with impairments in postural control and gross motor skills of children with developmental coordination disorder: a cross-sectional study. Medicine 94:e1785

Freyler K, Krause A, Gollhofer A, Ritzmann R (2016) Specific stimuli induce specific adaptations: sensorimotor training vs. reactive balance training. PLoS One 11:e0167557

Gambelli CN, Theisen D, Willems PA, Schepens B (2016) Human motor control of landing from a drop in simulated microgravity. J Appl Physiol (Bethesda, Md.: 1985) 121:760–770

Gollhofer A, Kyröläinen H (1991) Neuromuscular control of the human leg extensor muscles in jump exercises under various stretch-load conditions. Int J Sports Med 12:34–40

Gollhofer A, Strojnik V, Rapp W, Schweizer L (1992) Behaviour of triceps surae muscle–tendon complex in different jump conditions. Eur J Appl Physiol 64:283–291

Greenwood R, Hopkins A (1976) Landing from an unexpected fall and a voluntary step. Brain J Neurol 99:375–386

Günther M, Blickhan R (2002) Joint stiffness of the ankle and the knee in running. J Biomech 35:1459–1474

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G (2000) Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 10:361–374

Hoffer JA, Andreassen S (1981) Regulation of soleus muscle stiffness in premammillary cats: intrinsic and reflex components. J Neurophysiol 45:267–285

Hoffrén M, Ishikawa M, Rantalainen T, Avela J, Komi PV (2011) Age-related muscle activation profiles and joint stiffness regulation in repetitive hopping. J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol 21:483–491

Horak FB, Diener HC, Nashner LM (1989) Influence of central set on human postural responses. J Neurophysiol 62:841–853

Horita T, Komi PV, Nicol C, Kyröläinen H (2002) Interaction between pre-landing activities and stiffness regulation of the knee joint musculoskeletal system in the drop jump: implications to performance. Eur J Appl Physiol 88:76–84

Hughes G, Watkins J (2008) Lower limb coordination and stiffness during landing from volleyball block jumps. Res Sports Med (Print) 16:138–154

Ishikawa M, Komi PV (2004) Effects of different dropping intensities on fascicle and tendinous tissue behavior during stretch-shortening cycle exercise. J Appl Physiol (Bethesda, Md.: 1985) 96:848–852

Jidovtseff B, Quievre J, Harris NK, Cronin JB (2014) Influence of jumping strategy on kinetic and kinematic variables. J Sports Med Phys Fit 54:129–138

Kellis E, Arabatzi F, Papadopoulos C (2003) Muscle co-activation around the knee in drop jumping using the co-contraction index. J Electromyogr Kinesiol 13:229–238

Komi PV (1984) Biomechanics and neuromuscular performance. Med Sci Sports Exerc 16:26–28

Komi PV (2003) Stretch-shortening cycle. Strength Power Sport 2:184–202

Komi PV, Gollhofer A (1997) Stretch reflexes can have an important role in force enhancement during SSC exercise. J Appl Biomech 13:451–460

Konrad P (2006) The ABC of EMG: a practical introduction to kinesiological electromyography. Noraxon USA, Inc, Scottsdale

Kramer A, Ritzmann R, Gruber M, Gollhofer A (2012) Leg stiffness can be maintained during reactive hopping despite modified acceleration conditions. J Biomech 45:1816–1822

Kuitunen S, Kyrolainen H, Avela J, Komi PV (2007) Leg stiffness modulation during exhaustive stretch-shortening cycle exercise. Scand J Med Sci Sports 17:67–75

Kyrölänen H, Komi PV, Kim DH (1991) Effects of power training on neuromuscular performance and mechanical efficiency. Scand J Med Sci Sports 1:78–87

Lee RG, Tatton WG (1975) Motor responses to sudden limb displacements in primates with specific CNS lesions and in human patients with motor system disorders. Can J Neurol Sci (Le journal canadien des sciences neurologiques) 2:285–293

Leonhart R, Schornstein K, Groß J (2004) Lehrbuch Statistik. Einstieg und Vertiefung. Huber, Bern

Lesinski M, Prieske O, Beurskens R, Behm DG, Granacher U (2016) Effects of drop height and surface instability on neuromuscular activation during drop jumps. Scand J Med Sci Sports 27:1090–1098

Lesinski M, Prieske O, Beurskens R, Behm D, Granacher U (2018) Effects of drop-height and surface instability on jump performance and knee kinematics. Int J Sports Med 39:50–57

Leukel C, Taube W, Gruber M, Hodapp M, Gollhofer A (2009) Influence of falling height on the excitability of the soleus H-reflex during drop-jumps. Acta Physiol (Oxford, England) 192:569–576

Leukel C, Taube W, Lorch M, Gollhofer A (2012) Changes in predictive motor control in drop-jumps based on uncertainties in task execution. Hum Mov Sci 31:152–160

Márquez G, Morenilla L, Taube W, Fernández-del-Olmo M (2014) Effect of surface stiffness on the neural control of stretch-shortening cycle movements. Acta Physiol (Oxford, England) 212:214–225

Marsden CD, Merton PA, Morton HB, Adam JER, Hallett M (1978) Automatic and voluntary responses to muscle stretch in man. Prog Clin Neurophysiol 4:167

Mayer F, Baur H, Deibert P, Schmitt S, Gollhofer A (2007) Prävention von Verletzungen bei Stolper-, Rutsch- und Sturzunfällen. Einflussfaktoren von Fersenbeinfrakturen. Entwicklung einer Prüfapparatur und Evaluation präventiver Maßnahmen zur Verhütung von Fersenbeinfrakturen

McDonagh MJN, Duncan A (2002) Interaction of pre-programmed control and natural stretch reflexes in human landing movements. J Physiol 544:985–994

Miall RC, Wolpert DM (1996) Forward models for physiological motor control. Neural Netw 9:1265–1279

Moritz CT, Farley CT (2005) Human hopping on very soft elastic surfaces: implications for muscle pre-stretch and elastic energy storage in locomotion. J Exp Biol 208:939–949

Oliver JL, Smith PM (2010) Neural control of leg stiffness during hopping in boys and men. J Electromyogr Kinesiol Off J Int Soc Electrophysiol Kinesiol 20:973–979

Prieske O, Muehlbauer T, Mueller S, Krueger T, Kibele A, Behm DG, Granacher U (2013) Effects of surface instability on neuromuscular performance during drop jumps and landings. Eur J Appl Physiol 113:2943–2951

Prieske O, Muehlbauer T, Krueger T, Kibele A, Behm D, Granacher U (2015) Sex-specific effects of surface instability on drop jump and landing biomechanics. Int J Sports Med 36:75–81

Rinalduzzi S, Trompetto C, Marinelli L, Alibardi A, Missori P, Fattapposta F, Pierelli F, Currà A (2015) Balance dysfunction in Parkinson's disease. Biomed Res Int 2015:434683

Ritzmann R, Freyler K, Krause A, Gollhofer A (2016) Bouncing on Mars and the Moon-the role of gravity on neuromuscular control: correlation of muscle activity and rate of force development. J Appl Physiol (Bethesda, Md.: 1985) 121:1187–1195

Roelants M, Verschueren SMP, Delecluse C, Levin O, Stijnen V (2006) Whole-body-vibration-induced increase in leg muscle activity during different squat exercises. J Strength Cond Res 20:124

Schmidt RA (1968) Anticipation and timing in human motor performance. Psychol Bull 70:631

Serpell BG, Ball NB, Scarvell JM, Smith PN (2012) A review of models of vertical, leg, and knee stiffness in adults for running, jumping or hopping tasks. J Sports Sci 30:1347–1363

Silder A, Besier T, Delp SL (2015) Running with a load increases leg stiffness. J Biomech 48:1003–1008

Sinkjaer T, Toft E, Andreassen S, Hornemann BC (1988) Muscle stiffness in human ankle dorsiflexors: intrinsic and reflex components. J Neurophysiol 60:1110–1121

Sinkjaer T, Andersen JB, Nielsen JF, Hansen HJ (1999) Soleus long-latency stretch reflexes during walking in healthy and spastic humans. Clin Neurophysiol Off J Int Fed Clin Neurophysiol 110:951–959

Sousa F, Ishikawa M, Vilas-Boas JP, Komi PV (2007) Intensity- and muscle-specific fascicle behavior during human drop jumps. J Appl Physiol (Bethesda, Md.: 1985) 102:382–389

Taube W, Schubert M, Gruber M, Beck S, Faist M, Gollhofer A (2006) Direct corticospinal pathways contribute to neuromuscular control of perturbed stance. J Appl Physiol (Bethesda, Md.: 1985) 101:420–429

Taube W, Leukel C, Schubert M, Gruber M, Rantalainen T, Gollhofer A (2008) Differential modulation of spinal and corticospinal excitability during drop jumps. J Neurophysiol 99:1243–1252

Taube W, Leukel C, Gollhofer A (2012a) How neurons make us jump: the neural control of stretch-shortening cycle movements. Exerc Sport Sci Rev 40:106–115

Taube W, Leukel C, Lauber B, Gollhofer A (2012b) The drop height determines neuromuscular adaptations and changes in jump performance in stretch-shortening cycle training. Scand J Med Sci Sports 22:671–683

van Dieen JH, Kingma I, van der Bug P (2003) Evidence for a role of antagonistic cocontraction in controlling trunk stiffness during lifting. J Biomech 36:1829–1836

Viitasalo JT, Salo A, Lahtinen J (1998) Neuromuscular functioning of athletes and non-athletes in the drop jump. Eur J Appl Physiol 78:432–440

Wiley ME, Damiano DL (1998) Lower-extremity strength profiles in spastic cerebral palsy. Dev Med Child Neurol 40:100–107